

Department of Exploration Geophysics

**Integration of Depositional Process Modelling, Rock Physics and Seismic Forward
Modelling to Constrain Depositional Parameters**

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Master of Philosophy (Geophysics)
of
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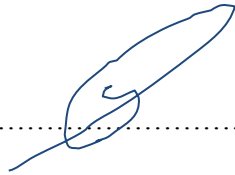
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DECLARATION

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ABSTRACT

SedSim, a numerical stratigraphic forward modelling package, which quantitatively and deterministically predicts variations in sediment distribution over time as the depositional environment changes, was used to generate a stratigraphic model over the Cornea field, Browse Basin, Australia. The target reservoir within the Cornea field is the Albian sandstones which form isolated sandstone bodies within siltstones and clay-rich sediments. Although numerical stratigraphic forward modelling is a powerful technique for predicting the subsurface, it comes with uncertainty. In order to identify and reduce the uncertainty in the stratigraphic model, this thesis proposed and applied the method of *closing the loop*, where the stratigraphic model over the Cornea field was integrated with the velocity-porosity-clay (VPC) rock physics model and the process of seismic forward modelling.

In this study, it took thirty one runs to generate the final SedSim model. Before each run, initial SedSim parameters had to be modified. Initially, during the earlier runs, uncertainty in the stratigraphic model was easily identified just by viewing the results. Initial SedSim parameters were then modified accordingly. However, as the stratigraphic model became more reasonable, uncertainty became difficult to identify.

The VPC rock physics model, which is suitable for clean sandstones as well as clay rich sandstones, was used to convert input from the stratigraphic model to elastic parameters. The elastic parameters were then used to calculate acoustic parameters. The acoustic parameters were used to generate synthetic seismic data via the process of seismic forward modelling. The simulated synthetic seismic data was then compared to its corresponding observed seismic data. The parameters of the generated SedSim stratigraphic model were modified based on the results of the comparison.

The process of closing the loop was successfully applied twice in this study. Once where sediments were deposited abruptly resulting in the formation of one thick interval. It was hard to see this in the

stratigraphic model but when the model was converted to seismic, uncertainty was identified by the absence of synthetic seismic reflections within that interval compared to observed seismic and initial Sedsim parameters were modified accordingly and the stratigraphic model was regenerated. During the second time, closing the loop revealed problems within a carbonate interval overlaying the target. It was concluded that one possible source for these problems was the application of the VPC rock physics model, designed for siliciclastics, within a carbonate interval. Other possible sources of error such as inaccurate initial Sedsim parameters are not to be excluded.

Ideally, another rock physics model, suitable for carbonate rocks, should be run within the carbonate interval. Then, the process of closing the loop should be applied to identify the source of the problem within the carbonate interval, whether it is from the VPC model or the initial Sedsim parameters, and reduce uncertainty to a satisfactory degree. However, due to the limited time given for this study, this was stated as a recommendation for future work.

Comparison between synthetic and observed seismic remained qualitative in this study. However, it was recommended to turn it into a quantitative process by inverting observed seismic data. Hence, one could perhaps in the future automate the process.

The process of closing the loop can be used to identify and reduce uncertainty in numerical stratigraphic modelling. The process of closing the loop is practical in terms of identifying uncertainty. However, finding the correct Sedsim parameters to modify in order to reduce the identified uncertainty in addition to re-running the Sedsim model can be time consuming. The run time problem can be overcome by reducing some Sedsim parameters such as grid size or by breaking the modelled area into smaller parts. In addition, the process of closing the loop came with by-products and applications that could be used utilized for other purposes.

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CHAPTER 1

INTRODUCTION

Synopsis

This chapter summarizes the motivation, objectives and workflow of this study. More details are available in the next chapters.

1.1 Motivation

Stratigraphic forward modelling (SFM) is a technique for predicting subsurface geology away from well data. Traditional stratigraphic forward modelling utilizes all available data including well logs and seismic interpretation. Then, “unknown gaps” in the subsurface geology e.g. at inter-well location are filled using geo-statistical methods such as interpolation and krigging (Bohling, 2005). In areas, where the wells are scarce or far apart or areas where there are significant lateral variations in the subsurface geology, geo-statistical methods are associated with significant uncertainty (Yarus, 2009).

Another type of stratigraphic forward modelling is numerical stratigraphic forward modelling. Numerical stratigraphic forward modelling attempts to predict the subsurface deterministically; starting at user-specified geologic time, numerical stratigraphic forward modelling software simulates depositional processes as time progresses from the user-specified geologic time to present time (Griffiths & Dyt, and Griffiths et al., 2001). However, many runs are required in order to create a reasonable stratigraphic model using this method. The resultant stratigraphic model needs to be assessed after each run. In other words, the uncertainty must be minimized after each run until satisfactory results are achieved. Therefore, a method via which uncertainty can be assessed and minimized is needed.

One way of evaluating the uncertainty of a numerical stratigraphic model is by generating synthetic seismic data from the stratigraphic model. The synthetic seismic data is then compared to corresponding observed seismic data over the same area. Based on the comparison results, initial

input parameters within the stratigraphic model are modified and the model is regenerated. This process is repeated until satisfactory results are achieved i.e. until uncertainty in the stratigraphic model is minimized. In this study, this process of generating a numerical stratigraphic model, generating synthetic seismic data from it, comparing it to its corresponding observed seismic data, regenerating the model based on the comparison results is referred to as *closing the loop*. This process is repeated until uncertainty in the model is minimized.

Al-Siyabi, Gurevich, and Madadi (2012) attempted to generate synthetic seismic data by integrating the VPC rock physics model and an existing SedSim-generated stratigraphic model. They found that the use of a low resolution stratigraphic model and a rock physics model that is unsuitable for the geological properties output by the stratigraphic model can negatively impact the generated synthetic seismic.

1.2 Objective

The main objective behind this study is to minimize uncertainty in the numerical stratigraphic model by closing the loop. During the process of closing the loop, synthetic seismic data, to be compared to observed seismic data, is generated from the stratigraphic model. Therefore the process of closing the loop allows for indirect comparison of the resultant numerical stratigraphic forward model with observed seismic data.

As secondary objectives, the final generated stratigraphic model can be used to constrain the number of possible realizations in stochastic inversion. In addition, many products that are generated during the process of closing the loop can be utilized for different applications.

1.3 Workflow

The first step in the workflow is to select a study area i.e. a geographical location where the study can be carried out. Once a study area is selected, a numerical stratigraphic forward modelling program is used to generate a numerical stratigraphic model over the study area. The program used in this study

is Sedsim. Sedsim was originally developed by Harbaugh's group in the 1980s at Stanford University. It has been enhanced by CSIRO group at the University of Adelaide since 1994 (Griffiths & Dyt, and Griffiths et al., 2001). When an initial Sedsim model is generated, it is converted to synthetic seismic (Figure 1.1).

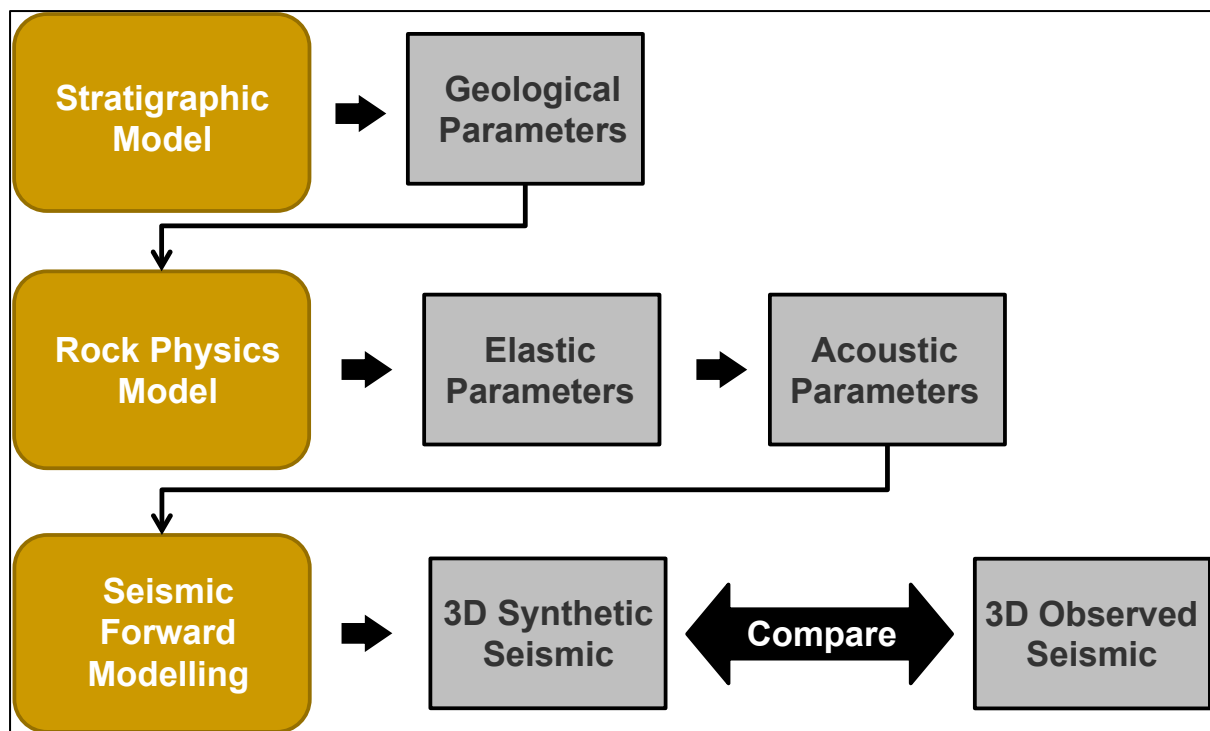


Figure 1.1: Workflow Chart: A chart summarizing the workflow of this study. First, a study area is selected. Then, a stratigraphic model over the selected area is generated. Geological parameters from the stratigraphic model are inputted into a rock physics model to generate elastic parameters. These are then used to calculate acoustic parameters. The acoustic parameters are converted to synthetic seismic via seismic forward modelling. Finally, the synthetic seismic data is compared with the observed seismic data.

In order to convert the generated Sedsim model to synthetic seismic, an existing rock physics model is utilized. The rock physics model is used to convert geological properties from the Sedsim model to elastic properties. These elastic properties are used to calculate acoustic properties. Via seismic forward modelling, the acoustic properties are used to generate synthetic seismic data.

When synthetic seismic data is finally generated, it is compared to observed seismic data over the same area, the study area. Sedsim initial parameters are modified based on this comparison and the

program is re-run to generate an updated Sedsim model. This process, closing the loop, is repeated until a “good match” between synthetic and observed data is achieved i.e. the uncertainty in Sedsim model is minimized.

CHAPTER 2

BACKGROUND

Synopsis

This chapter illustrates the research plan via which the objective is achieved. In addition, it reviews some basic concepts needed to understand the objective.

2.1 Stratigraphic Forward Modelling

Stratigraphic modelling can be used to predict the subsurface. It attempts to create a three dimensional representation or a realization of an area of the subsurface based on geological and geophysical observations. Geological observations usually include data from well logs while geophysical observations are usually based on the interpretation of seismic data.

A modern stratigraphic modelling program should be able to integrate all available data in order to create a model of rock layering and properties at some required resolution in three dimensions (Fallara, Legault & Rabeau, 2006). Some programs start by building a structural framework using interpretation results e.g. fault polygons and horizons from seismic data. Well log data are then incorporated in the model to add information on geological properties such as porosity, lithology and fluid saturation (Yarus, 2009).

The stratigraphic model is divided into a number of cells. The more cells, the higher resolution of the stratigraphic model and the finer the features it can resolve.

When all available geological and geophysical data are incorporated into the stratigraphic model, geo-statistical methods are used to populate these cells. Geo-statistical methods such as interpolation and kriging are used to fill in the gaps in areas where there is no data (Bohling, 2005).

2.2 Traditional Stratigraphic (or Geo-cellular) Modelling

Since the 1980's oil-field stratigraphic modelling ('static modelling') has primarily used geo-statistical methods.

A typical task for a traditional modelling approach is to interpolate sediment properties between two or more wells by applying geo-statistical methods using data from these wells as input. Other types of input including seismic data, and previously known geological information, are also utilized. In this case the accuracy of the stratigraphic model is usually dependent on the quality and availability of input data. Therefore, in areas where data is of relatively low quality or quantity, the resultant stratigraphic model comes with large uncertainty (Yarus, 2009).

2.3 Numerical Stratigraphic Forward Modelling

Unlike traditional stratigraphic modelling, numerical stratigraphic forward modelling does not rely on geo-statistical methods. A numerical SFM program is able to quantitatively model the changes in sedimentation process with time in order to predict rock properties away from well data. A numerical SFM program usually starts with a given geological time and geological parameters. It then simulates the sedimentation process as time progresses and as the depositional environment changes (Griffiths & Dyt, and Griffiths et al., 2001).

A numerical SFM program divides the stratigraphic model into cells similar to those created by a traditional stratigraphic modelling program. However, these cells are not populated using geo-statistical methods. Instead, they are populated deterministically using palaeo-environment and palinspastic reconstruction knowledge over a user-specified geological time interval rather than depth intervals (Griffiths & Dyt, and Griffiths et al., 2001).

The deterministic approach of numerical forward stratigraphic modelling makes it less reliant on the availability of geological and geophysical data at well locations. In addition, it reduces possible bias towards "hard data" such as well logs, which can result in uncertainty in areas with sparse wells or

where there are large subsurface variations. Consequently, numerical stratigraphic forward modelling comes with uncertainty that is more uniform and testable than traditional stratigraphic geo-cellular modelling (Griffiths & Dyt, and Griffiths et al., 2001).

Numerical stratigraphic Forward Modelling (NSFM) is a sedimentary process simulation that replays the way that stratigraphic successions develop and are preserved. It reproduces numerically the physical processes that eroded, transported, deposited and modified the sediments over varying time periods. In a forward modelling approach, data are not used as the anchor points for facies interpolation or extrapolation, but to test and validate the results of the simulation. Stratigraphic forward modelling is an iterative approach, where input parameters have to be modified until the results are validated by actual data. One of the major benefits of using NSFM to characterize sedimentary successions is the fact that, unlike with geo-statistical approaches, the results will always make sense from a geological point of view. It is also possible to test different geological scenarios, environments or conceptual models, to assess their impact on the stratal geometry and better understand the depositional processes. Ultimately, it enables the prediction of facies and porosity distributions in areas where data are sparse, unevenly distributed, or at inappropriate resolution (Griffiths & Dyt, and Griffiths et al., 2001).

2.4 Sedsim Introduction

Sedsim is a three-dimensional stratigraphic forward modelling program. It was originally developed in the 1980s at Stanford University by D. Tetzlaff and J. Wendebourg under the supervision of Prof. J. Harbaugh. Since 1994, the program has been undergoing modifications and enhancement at the University of Adelaide and at the Commonwealth Scientific and Industrial Research Organization (CSIRO) by C. Dyt, F. Li and T. Salles (Griffiths & Dyt, and Griffiths et al., 2001).

Sedsim is at its core a numerical hydraulic-process based computer program. This means that Sedsim quantitatively predicts variations in sediment distribution over geological time as the depositional environment changes. This is achieved deterministically by applying fluid flow equations to a range

of geological parameters determined from palaeo-environment and palinspastic reconstructions over a user-specified geological time interval (Griffiths & Dyt, and Griffiths et al., 2001). In other words, Sedsim starts at a user-specified geological time and replays the sedimentation processes as geological time progresses and as depositional environment changes. The program can simulate various siliciclastic and carbonate depositional processes on a given bathymetric surface.

Sedsim employs approximations to solutions of the Navier-Stokes equations in order to numerically simulate fluid flow and sediment erosion, transport and deposition. The full Navier-Stokes equations are currently impossible to solve. Therefore the equations are simplified within Sedsim and are solved using a marker-in-cell approach using a combined Eulerian and Lagrangian representation of fluid flow. The fluid flow is simulated in two horizontal dimensions while flow velocities are assumed to be uniform in the vertical direction (so-called 2D-depth-averaged flow). In this case, the velocity of the fluid body as a whole remains constant but can change in horizontal directions. Fluid flow velocity and sediment load are represented by points within the fluid body that move with the flow. At a given time, a point or marker contains information including fluid flow velocity, sediment load and fluid element position. This information is recalculated and updated at each time step (Griffiths & Dyt, and Griffiths et al., 2001).

Within Sedsim there are core programs and sub-programs or computational modules. The core programs are related to fluid flow and sedimentation. Some of the computational modules are linked to the core programs while others are executed separately. The computational modules include subsidence, sea level change, wave transport, compaction, slope failure, carbonates and organics (Figure 2.1) (Griffiths & Paraschivoiu, 1998).

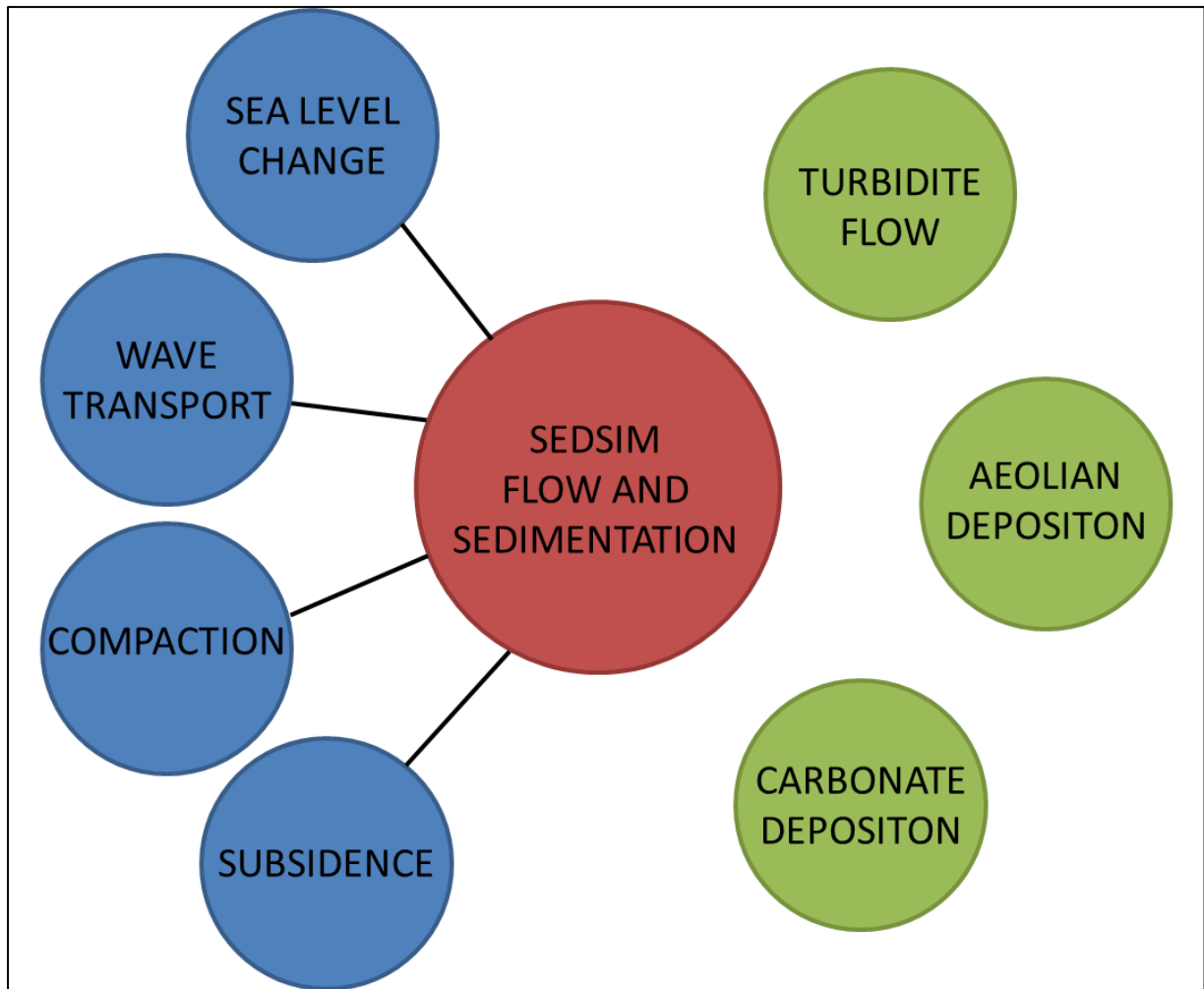


Figure 2.1: An illustration showing computational modules that are linked to Sedsim core program (Sea Level, Wave Transport, Compaction and Subsidence) and computational modules that are run separately (Turbidite Flow, Aeolian Deposition and Carbonate Deposition).

In addition to core programs and modules, user-input data, which control fluid flow and sedimentation processes, can be fed into Sedsim. The user-input data can be divided into two parts: Sedsim parameters and additional input. Each module in Sedsim contains a set of parameters that can be specified or modified by the user. These parameters include (among many others) sediment and river source location, fluid density, fluid velocity, wave direction, and sea level curve (Griffiths & Paraschivoiu, 1998). Many of these parameters can be derived from the literature while others involve

iterative testing until Sedsim output matches well and seismic stratal geometries to an acceptable degree.

Sedsim does not use well logs or seismic horizons as input data but a seismic horizon is often used as a starting or basal surface, a bathymetric surface on which Sedsim begins the hydraulic flow process. This surface may be initially derived from a seismic horizon representing e.g. an unconformity surface but it often needs some palinspastic reconstruction to correctly reflect hydraulic flow gradients and directions (Figure 2.2) (Griffiths and Dyt, 2001).

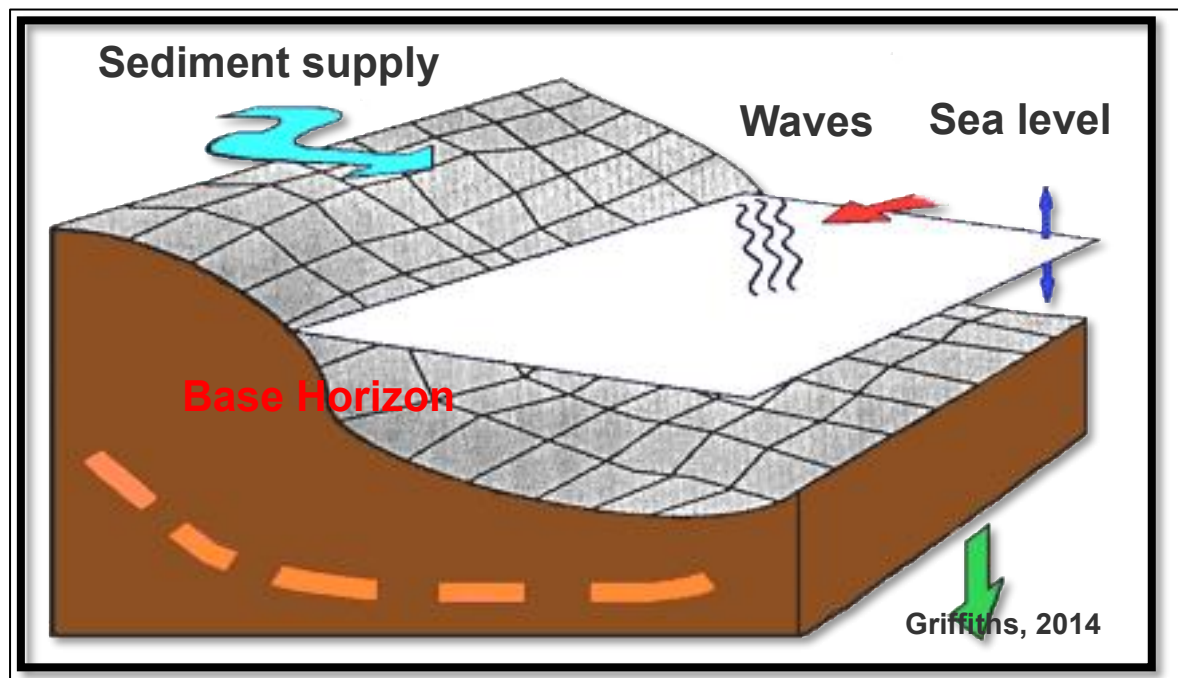


Figure 2.2: Sedsim user-input data includes parameters within Sedsim modules such as Waves and Sea Level. In addition, user-input may include a seismic-derived surface, base horizon, on which Sedsim can begin the hydraulic flow process.

Several runs are usually required before Sedsim output matches observations to a pre-specified degree at well locations. Before each run, initial input parameters are modified through a text file. The text file is run in Sedsim. The result, the stratigraphic model, is generated in the form of a set of files and is displayed using the SedView viewer external to Sedsim. The computational time and intensity for

each run varies depending on the input parameters and input data. A large grid size, or many modules, for example, will increase the computational time and intensity (Griffiths & Dyt, 2001).

The resultant Sedsim stratigraphic model is three-dimensional grid node volume; the vertical axis is in either depth or geological time, the horizontal axes are in distance while the value at each node is a selected geological property such as porosity, grain size and geological age. Each node in the model has a UTM coordinate location and contains quantitative information concerning geological properties such as porosity and grain size at different depths (Figure 2.3). The number of the nodes and the distance between them are specified in the input parameters (Griffiths & Dyt, 2001).

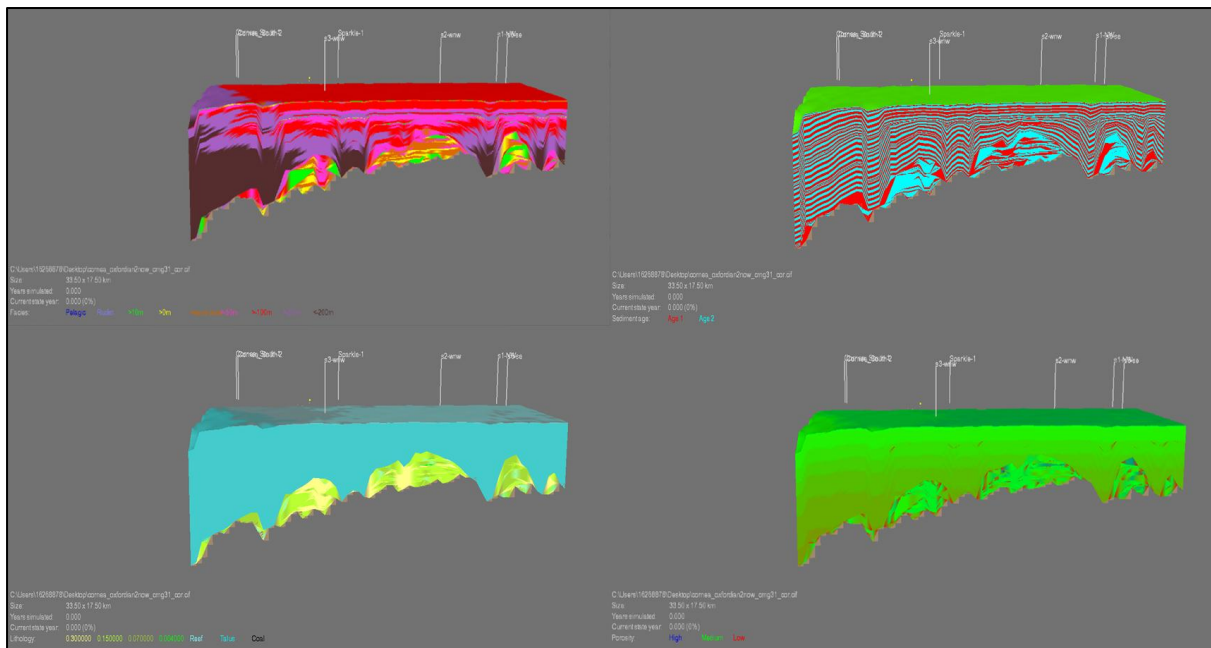


Figure 2.3: Sedsim stratigraphic model example: the vertical axis is depth in meters, the horizontal axes are distance in meters and the node values are: lithofacies (top-left), alternating age (top-right), lithology (bottom-left) and porosity (bottom-right).

2.5 Uncertainty in Numerical Stratigraphic Forward Modelling

Although numerical stratigraphic forward modelling is a powerful technique, it is important to constrain and minimise the uncertainty in the resultant stratigraphic model. The process of creating a stratigraphic forward model using a numerical stratigraphic forward modelling program usually

requires several runs before Sedsim output matches observations to a pre-specified degree at well locations. Before each run, initial input parameters are modified. A process is needed in order to determine whether the output is satisfactory and which parameters to modify. In other words, we need a process by which the uncertainty in the output can be constrained.

2.6 “Closing the loop” As A Method To Minimize Uncertainty

One approach to reducing the uncertainty in a stratigraphic model is by comparing it to observed seismic data. The stratigraphic model is then modified based on the results of the comparison. However, a comparison between a stratigraphic model and observed seismic is not valid since the two are of different parameters. This problem can be overcome by simulating synthetic seismic data from the stratigraphic model. The simulated synthetic seismic data is then compared to observed data over the same area. This allows for a comparison between the results of the stratigraphic model and the observed seismic data, which in turn can be used to tune or modify the initial parameters of the stratigraphic model (i.e., closing the loop) and thus reduce the uncertainty of the stratigraphic model (Figure 2.4).

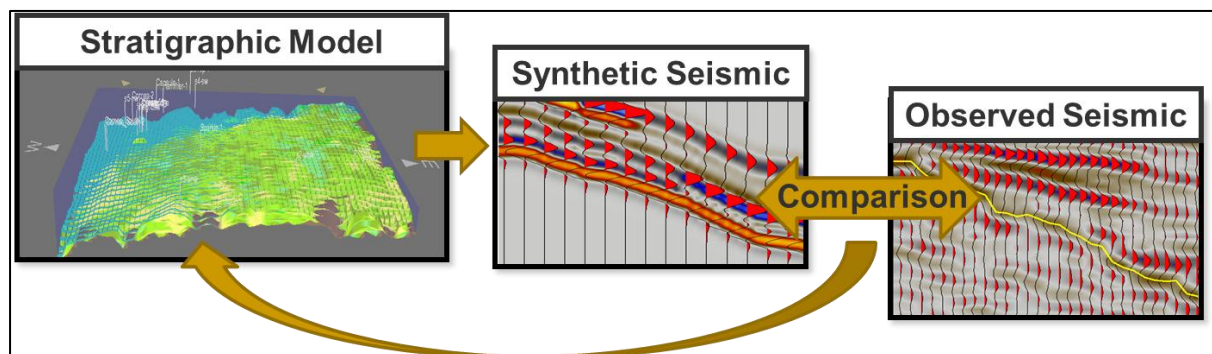


Figure 2.4: Uncertainty in the stratigraphic model can be minimized by closing the loop: comparing synthetic seismic data derived from a stratigraphic model with corresponding observed seismic data and modifying the initial stratigraphic model parameters based on the results of the comparison.

The process of closing the loop is usually repeated several times until a satisfactory result is obtained i.e. until a satisfactory match between the simulated synthetic seismic and the observed seismic is obtained.

2.7 The Problem of Input

So far, I have proposed comparing the generated stratigraphic model to observed seismic as a method to reduce the uncertainty in the stratigraphic model. As explained above, this is done via the process of closing the loop: simulating synthetic seismic data from the stratigraphic model. One can then compare the generated synthetic seismic data to the observed seismic data. The stratigraphic model is then modified until a good match between the two data sets, synthetic and observed, is achieved.

One problem that may arise during such comparison is what I like to refer to as the “problem of input”. During the generation of a stratigraphic forward model, geophysical data mainly from the observed seismic data are used as initial input. This means that the stratigraphic forward model will be influenced by input data from the observed seismic before any comparison is made. Consequently, a good match between synthetic seismic data (generated from the stratigraphic forward model) and observed seismic data could be a result of the geophysical input data from the observed seismic and not necessarily an indication of the accuracy of the stratigraphic forward model (Figure 2.5).

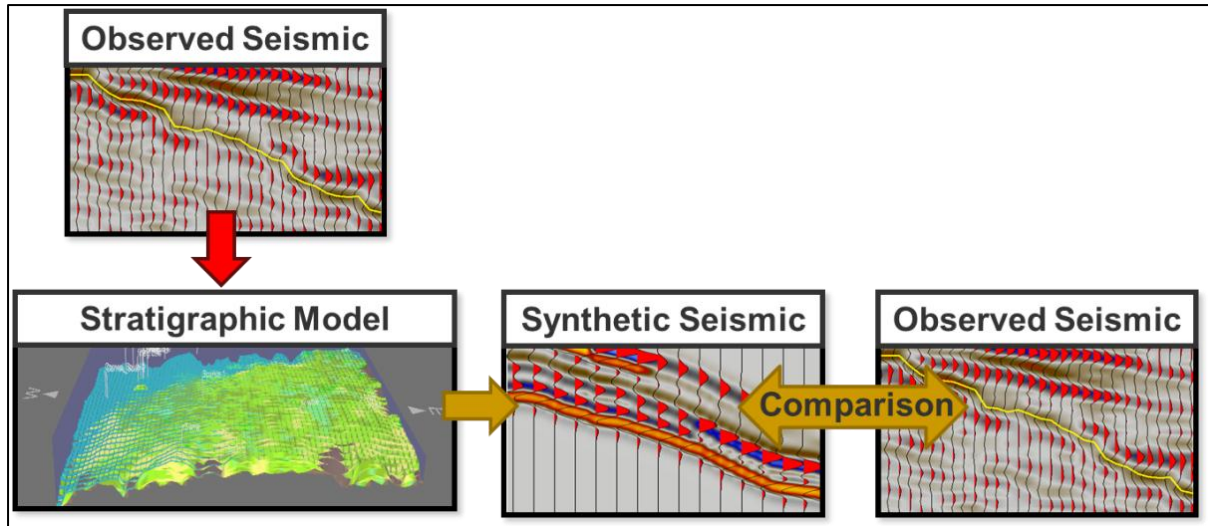


Figure 2.5: The Problem of Input: When observed seismic data is used initially as input into the stratigraphic model, it is passed to the synthetic seismic data generated from the stratigraphic model. Therefore, any match or mis-match between synthetic and observed seismic data may be attributed to initial observed seismic input and not to the quality of the stratigraphic model.

Geophysical data used in this simulation consisted of one seismic horizon corresponding to one reflection boundary in the observed seismic data and to the base of a stratigraphic layer. This horizon is used as base level on top of which the stratigraphic model is built. The remaining layers in the stratigraphic model, which are above this horizon, are deterministically generated without any seismic input. In addition, no other type of seismic or seismic-derived attribute input is used in the generation of the stratigraphic forward model. This way, any match or mismatch between synthetic seismic generated from the stratigraphic model data and observed seismic data is indicative of the accuracy of the stratigraphic forward model and not a result of geophysical input from observed seismic.

2.8 Seismic Forward Modelling

A 3D seismic volume consists of seismic traces. Each one of these traces consists of a series of amplitudes. Seismic amplitude results from the convolution of a wavelet and a reflection coefficient at an earth boundary. A reflection coefficient at an earth boundary is calculated if the velocities and densities above and below the boundary are known.

Seismic forward modelling is the process by which synthetic seismic data is generated. Therefore, in seismic forward modelling, we usually start from an earth model and use it to generate seismic data.

Figure 2.6 below illustrates how a seismic trace is generated from an earth model through the convolutional model (Kearey, Brooks & Hill, 2002).

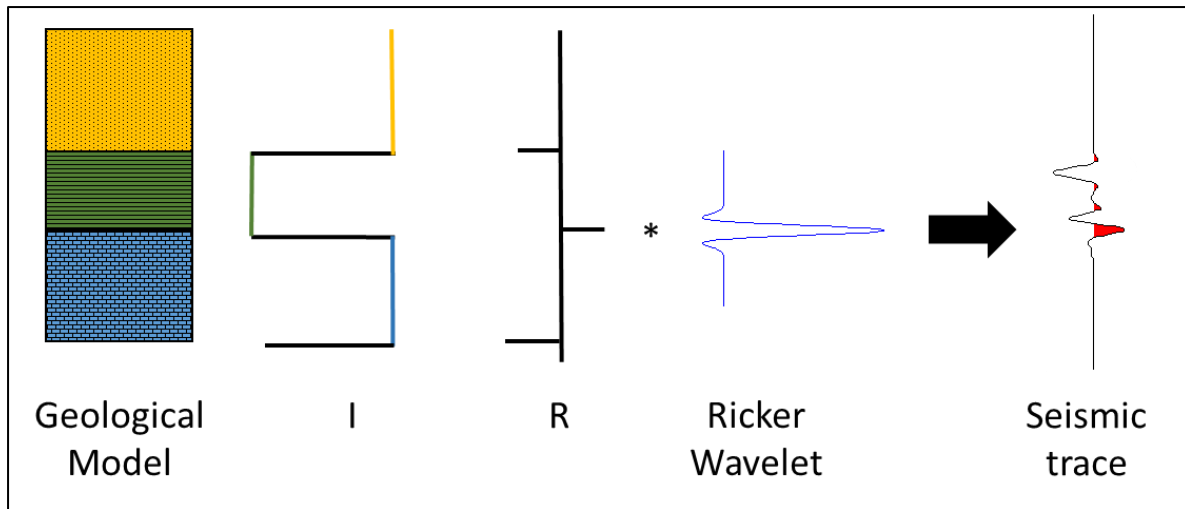


Figure 2.6: Seismic forward modelling starts with a geological model. If velocities and densities of each layer within the geological model are known, acoustic impedance (I) can be calculated for each layer. Reflection coefficients (R) can then be calculated at each boundary. Reflection coefficients can be used to calculate a reflectivity function. A seismic trace is the output of the convolution (*) of a wavelet (Ricker Wavelet in this case) with the reflectivity function. Note that the seismic trace in this figure is not generated from the geological model in the figure. It is only used to illustrate the general concept of the convolutional model.

For further clarification, a double-layered earth model is considered where there are two distinct subsurface layers: layer 1 and layer 2. If layer 1 has a velocity V_1 and density ρ_1 , while layer 2 has a velocity V_2 and density ρ_2 (Figure 2.7).

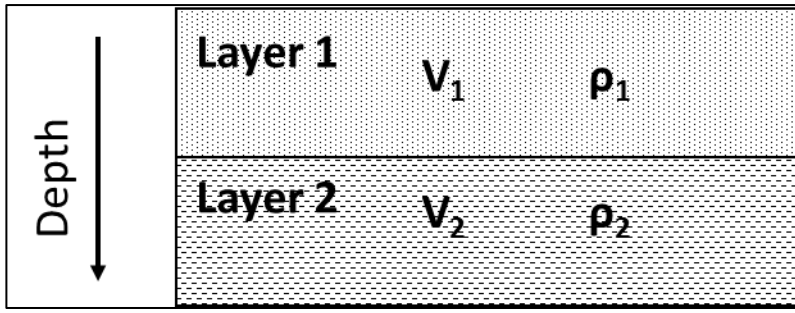


Figure 2.7: A simple two-layer earth model.

The reflection coefficient R at the boundary between the two layers can be calculated using the equation:

$$R = \frac{I_2 - I_1}{I_2 + I_1} \quad (1)$$

where I_1 , known as the acoustic impedance of layer 1, is the product of the velocity and density of layer 1 and I_2 , the acoustic impedance of layer 2, is the product of the velocity and density of layer 2. Once the reflection coefficient is calculated, then it can be convolved with a wavelet e.g. a Ricker wavelet in order to generate seismic amplitude and hence seismic trace or a pulse in this case.

The example above shows that knowledge of velocity and density at each layer is necessary to calculate acoustic impedances at each layer and thus generate seismic data. Since this is an example, I assume that both velocity and density at each layer are known from the earth model but this is not usually the case.

2.9 Traditional Seismic Forward Modelling

Let's consider the same example above. Only this time, let's assume we have a 3D stratigraphic model instead of the simplistic double-layered earth model above and from which, we are trying to generate a 3D synthetic seismic volume instead of a single trace. A stratigraphic model usually contains information on the subsurface geologic parameters e.g. density. Therefore, density values can

be derived from the stratigraphic model. However, stratigraphic models do not usually contain subsurface velocity information. Traditionally, well log data has been utilized in order to overcome this problem. Well logs, namely sonic logs, can provide measurements of the velocity of the subsurface around the borehole location (Anderson & Cardimona). Geo-statistics e.g. interpolation is then utilized for inter-well locations. A velocity volume or cube is then generated based on the results of geo-statistics. Velocity values from the velocity cubed are then multiplied with their corresponding density values from the stratigraphic model to generate an acoustic impedance volume. The acoustic impedance volume is utilized to calculate a reflectivity volume and finally the reflectivity volume is convolved with a wavelet in order to generate the desired output: a synthetic seismic volume. This example, again, shows that velocity information is central to seismic forward modelling. It also illustrates one approach to get velocity information, the traditional approach, which mainly utilizes well log data and geo-statistical methods.

Geo-statistical methods have been accepted as a way to “fill in the gaps” and sometimes give good results. However, they can be associated with large uncertainty, especially in situations where the subsurface velocities have significant lateral variation and where there are only a few or no wells. Therefore, a more deterministic approach of determining the subsurface velocities is needed.

2.10 The Application of Rock Physics in Seismic Forward Modelling

Rock physical methods attempt to find a link between geological properties and geophysical properties of rocks. This is done via a rock physics model. A rock physics model usually consists of an equation or a set of equations, which attempt to link the geological and geophysical properties of rocks for a given geological scenario. Various rock physics models have been derived for various geological scenarios but they share the same basic method. They usually start with some knowledge of the geological properties of the rock such as the constituent mineral components and porosity. They, then, use this knowledge to calculate the elastic properties of rocks. The elastic properties of rocks a rock physics model usually calculates are the Bulk modulus K , the shear modulus μ and the density ρ . The elastic properties are then used to calculate geophysical properties i.e. velocities. The

elastic parameters can be calculated for various saturation scenarios by the fluid substitution method using Gassmann's equation (Avseth, Mukerji & Mavko, 2005).

Let's go back to the previous example, where we are starting with a 3D stratigraphic model and would like to use to generate a synthetic seismic volume. Only this time instead of calculating a velocity cube using well log data and geo-statistical methods, we use a rock physics model. In this case, for each node in 3D the stratigraphic model, we can use known geological properties e.g. consistent mineral components and porosity as input for the rock physics model. The rock physics model can then use these geological properties to calculate elastic parameters. These elastic parameters can then be used to calculate velocities. Velocity values at each node can be multiplied by their corresponding density values to calculate acoustic impedance values. Acoustic impedance values are used to calculate reflectivity. Finally, reflectivity is convolved with a wavelet to generate a synthetic seismic trace for each node of the 3D stratigraphic model. Since each node location corresponds to a seismic trace location, a synthetic seismic volume can be generated by repeating this process for each node in the 3D stratigraphic model.

The advantage of applying a rock physics model in determining the subsurface velocities is that, unlike geo-statistical methods, it is a deterministic approach that is independent of well log data availability. Consequently, it comes with less uncertainty compared to geo-statistical methods especially in areas where wells are sparsely located or there are large subsurface velocity variations.

2.11 The Velocity-Porosity-Clay (VPC) Rock Physics Model Background

The Velocity-Porosity-Clay (VPC) rock physics model is an extension of the Velocity-Porosity rock physics model proposed by Krief et al. Krief et al. Velocity-Porosity model works well for clean porous fluid-saturated rocks. It assumes that the compressional and shear velocities of such rocks obey Gassmann's equations with the Biot compliance coefficient. In particular, Krief et al. Velocity-Porosity model assumes that the Bulk Biot compliance coefficient can be given by a function of porosity (Goldberg & Gurevich, 1998):

$$1 - B = (1 - \Phi_{total})^{\frac{A}{(1 - \Phi_{total})}} \quad (2)$$

, where B is the Biot compliance coefficient, Φ_{total} is the total porosity and A is a dimensionless empirical coefficient.

Therefore, given porosity information, the model can be used to calculate the compressional and shear velocities of clean porous fluid-saturated rocks using Gassmann's equations and the standard compressional and shear velocities formulae (Goldberg & Gurevich, 1998):

$$K_{sat} = K_{dry} + B^2 M \quad (3)$$

$$\mu_{sat} = \mu_{dry} \quad (4)$$

$$M = \left(\frac{B - \Phi_{total}}{K_s + \frac{\Phi_{total}}{K_{fluid}}} \right)^{-1} \quad (5)$$

$$V_p = \sqrt{\frac{(K_{sat} + \frac{4}{3} \mu_{sat})}{\rho_{sat}}} \quad (6)$$

$$V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \quad (7)$$

$$\rho_{sat} = \rho_{effective} (1 - \Phi_{total}) + \rho_{water} \Phi_{total} \quad (8)$$

, where K_{dry} and K_{sat} are the bulk moduli of the dry and saturated rocks, respectively, B is Biot compliance coefficient, M is the pore-space modulus, μ_{dry} and μ_{sat} are the shear moduli of the dry and saturated rocks, respectively, Φ_{total} is the total porosity, K_s is the solid grains bulk modulus,

K_{fluid} is the bulk modulus of the saturating fluid, V_p is the compressional wave velocity, V_s is the shear wave velocity, ρ_{sat} , $\rho_{effective}$ and ρ_{water} are the densities of the saturated rock, effective solid grains and the saturating fluid, respectively.

In order to be able to use Krief et al. Velocity-Porosity model for clay-rich fluid saturated rocks, the VPC model assumes that the bulk and shear moduli of the grain material and the dependence of compliance on porosity are both functions of clay content. The first assumption is achieved by computing a non-porous mixture of sand and clay using the lower Hashin-Shtrikman bound (Goldberg & Gurevich, 1998):

$$K_{effective} = K_{clay} + \frac{(1 - C)(K_{sand} - K_{clay})}{1 + C(K_{sand} - K_{clay})/(K_{clay} + \frac{4}{3}\mu_{clay})} \quad (9)$$

$$\mu_{effective} = \mu_{clay} + \frac{(1 - C)(\mu_{sand} - \mu_{clay})}{1 + C(\mu_{sand} - \mu_{clay})/(\mu_{clay} + \frac{4}{3}\mu_u)} \quad (10)$$

, where $K_{effective}$, K_{sand} and K_{clay} are the bulk moduli of the effective rock, sand and clay respectively, μ_{sand} and μ_{clay} are the shear moduli of sand and clay, respectively, C is clay content and $\mu_u = \frac{3}{2} \left(\frac{1}{\mu_{clay}} + \frac{10}{9K_{clay} + 8\mu_{clay}} \right)^{-1}$.

The second assumption is achieved by re-writing the empirical constant A in Krief et al. compliance-porosity function as:

$$A = A_0 + A_1 C^2 \quad (11)$$

, where A is Krief's empirical constant, A_0 and A_1 are empirical constants introduced by the VPC model and C is clay content.

Hence, introducing clay content as a parameter within Krief et al. compliance-porosity function. Like Krief et al. Velocity-porosity model, the VPC model obeys Gassmann's equations with the Biot compliance coefficient. Therefore, the VPC model can be used to calculate compressional and shear velocities for clay-rich sands using Gassmann's equations and the standard compressional and shear velocities formulae, as well (Goldberg & Gurevich, 1998).

Some parameters used as input for the VPC model are determined using available data within the area of interest. In particular, K_{clay} , μ_{clay} and A_0 are determined using a multivariable non-linear regression fit. Therefore, the VPC model is semi-empirical (Goldberg & Gurevich, 1998):

$$S = \frac{1}{N} \sum_{i=1}^N \{ [V_P(\phi_i, C_i) - V_{Pi}]^2 + \omega [V_S(\phi_i, C_i) - V_{Si}]^2 \} \quad (12)$$

, where S is the mean-square deviation, $V_P(\phi, C)$ and $V_S(\phi, C)$ are the compressional wave and shear wave velocities calculated using the VPC model, respectively, ϕ is porosity, C is clay content, ω is a dimensionless constant that defines the weight given to shear wave velocities compared to compressional wave velocities.

2.12 Synthetic vs. Observed Seismic Data Comparison

A comparison between two seismic volumes is not as simple as it may sound. In fact, it can be complex. In this study there are two main factors that contribute to the complexity of such problem. These factors are the fact that this is a comparison between synthetic seismic and observed seismic data and that a quantitative comparison method is desired.

Synthetic and observed seismic inevitably differ in some aspect, no matter how great the match between them. This is because synthetic seismic data is “ideal” i.e. it is usually free of noise such as linear noise and multiples whereas observed seismic data is not. This can be illustrated by generating a synthetic seismic trace from well log data and comparing this generated trace to its corresponding observed one. Although the synthetic seismic trace may accurately represent the subsurface and more importantly corresponds to the observed seismic trace, the two traces will probably look different.

Consequently, a comparison between synthetic and seismic data cannot be “strict”. In other words, a good match between synthetic and observed seismic data does not necessarily require that the two data sets, synthetic and observed, look exactly the same. However, for a good match, the two data sets must not look too different. Based on the above, the definition I have so far for a “good match” between synthetic and observed seismic data is that they don’t necessarily have to look exactly the same but they must not look too different. A better and more quantitative definition is needed. This leads us to the second main factor.

The other main factor that contributes to the complexity of the comparison between synthetic and observed seismic data is the desire to have a quantitative method of comparison between them. A quantitative method of comparison expresses the comparison results in terms of numbers.

One quantitative method of comparison between two seismic data sets is trace-by-trace cross correlation. In this method, each trace from a seismic data set is cross correlated with its corresponding trace in the other seismic data set. The result of the comparison is expressed by a number. The higher the number the better the match. A cut-off number can be chosen for this method below which, no good match is achieved.

Unfortunately, since the comparison in this study is between two data sets that will inevitably differ even when a good match is achieved, cross correlation may not work. This is because cross correlation may be too strict, assigning values that are too low for cases where there is a good match.

A better way to compare observed and synthetic seismic data is by first inverting observed seismic data to acoustic impedance. The observed acoustic impedances are then compared with the synthetic acoustic impedances. Due to time constraints, the observed seismic data is not inverted. Therefore, the comparison is qualitative while quantitative observed versus synthetic acoustic impedance comparison is listed as a recommendation for future work.

CHAPTER 3

STUDY AREA

Synopsis

This chapter is an overview of the study area in terms of the most relevant existing geological, geophysical and petrophysical data.

3.1 The Cornea Field: Geological Background

The Cornea Field is an unproduced offshore oil field located within the inner part of the Browse basin and across the Yampi shelf in the northwestern part of Australia (Figure 3.1). Albian sediments within the Cornea field overlay relatively shallow Pre-Aptian Basement forming a four-way dip closure (Moby Oil and Gas Ltd, 2009).

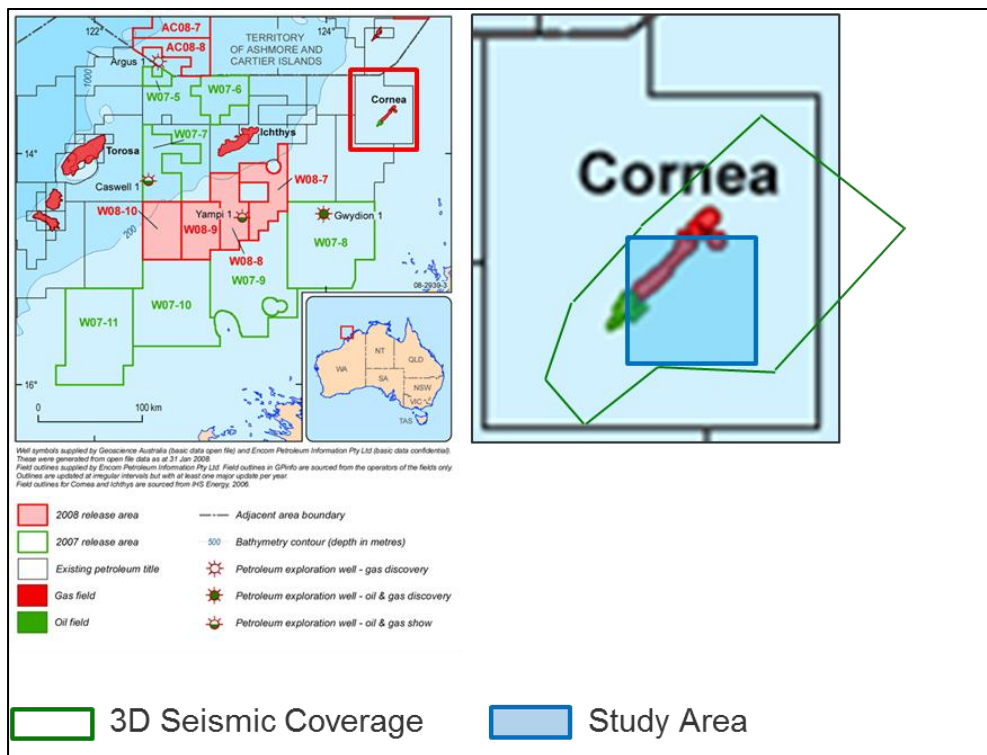


Figure 3.1: The Cornea field is an offshore field situated within the Browse basin, NW of Australia (left). The field is covered by 3D seismic data and the study area was selected within the 3D seismic coverage (right). © Commonwealth of Australia (Geoscience Australia) 2015. This product is released under the Creative Commons Attribution 4.0 International Licence. <http://creativecommons.org/licenses/by/4.0/> (edited).

Since the 1997 Cornea-1 discovery well, the Albian sandstones within the Cornea Field and the Browse basin, have become a target for hydrocarbon exploration.

Albian sediments in this area range from siltstones to sandstones. The Albian sandstones form isolated sandstone bodies within siltstones and clay-rich sediments (Figure 3.2). In addition, some of these sandstones are non-hydrocarbon bearing. Thus, detecting the Albian sandstones and predicting their hydrocarbon reservoir potential is challenging (Moby Oil and Gas Ltd, 2009).

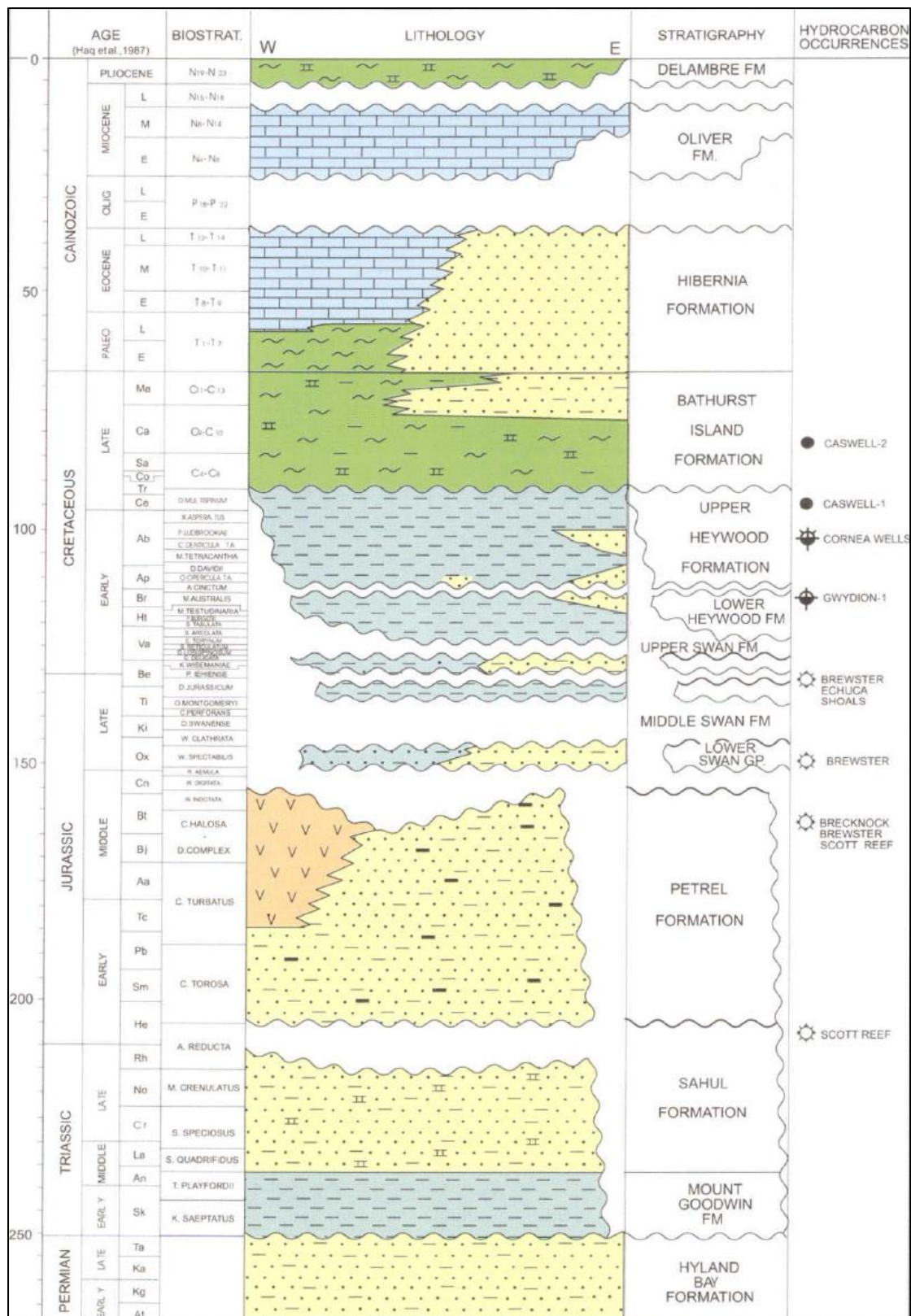


Figure 3.2: Target Reservoir: Albian (Ab) sands form the main target within the Cornea field. They form sandstone bodies (yellow) within shale and siltstones (blue). © Commonwealth of Australia (Geoscience Australia) 2015. This product is released under the Creative Commons Attribution 4.0 International Licence. <http://creativecommons.org/licenses/by/4.0/> (edited).

A description of the Cornea field was published by Shell Development Australia (SDA) in 2000. SDA's interpretation divides the Albian sediments into five units based on core and log data. The five units are (from top to bottom) (Moby Oil and Gas Ltd, 2009) (Figure 3.3):

- Seal: Extensive marine shale of Albian age.
- Unit A: 9.6 m thick waste zone just below the reservoir. This layer contains claystones and siltstones grading to sandstone. The estimated porosity of this layer is 3% based on core measurements.
- Unit B: 10 m thick reservoir interval. This layer is composed of sandstones with an estimated visual porosity of 10% based on core.
- Unit C: 10 m thick reservoir interval. This layer is composed of siltstones and sandstone with an estimated visual porosity of 10% based on core.
- Unit D: 14.1 m thick very clay rich non-reservoir interval. It is composed of claystones and silty sandstones with a porosity of less than 3%.

A full description of the depositional environment can be found in Appendix K.

It is worth mentioning that the porosities above are based on core visualization and were not used as input into the rock physics model. Total porosities from Sedsim stratigraphic model were used instead as will be detailed in the next chapters.

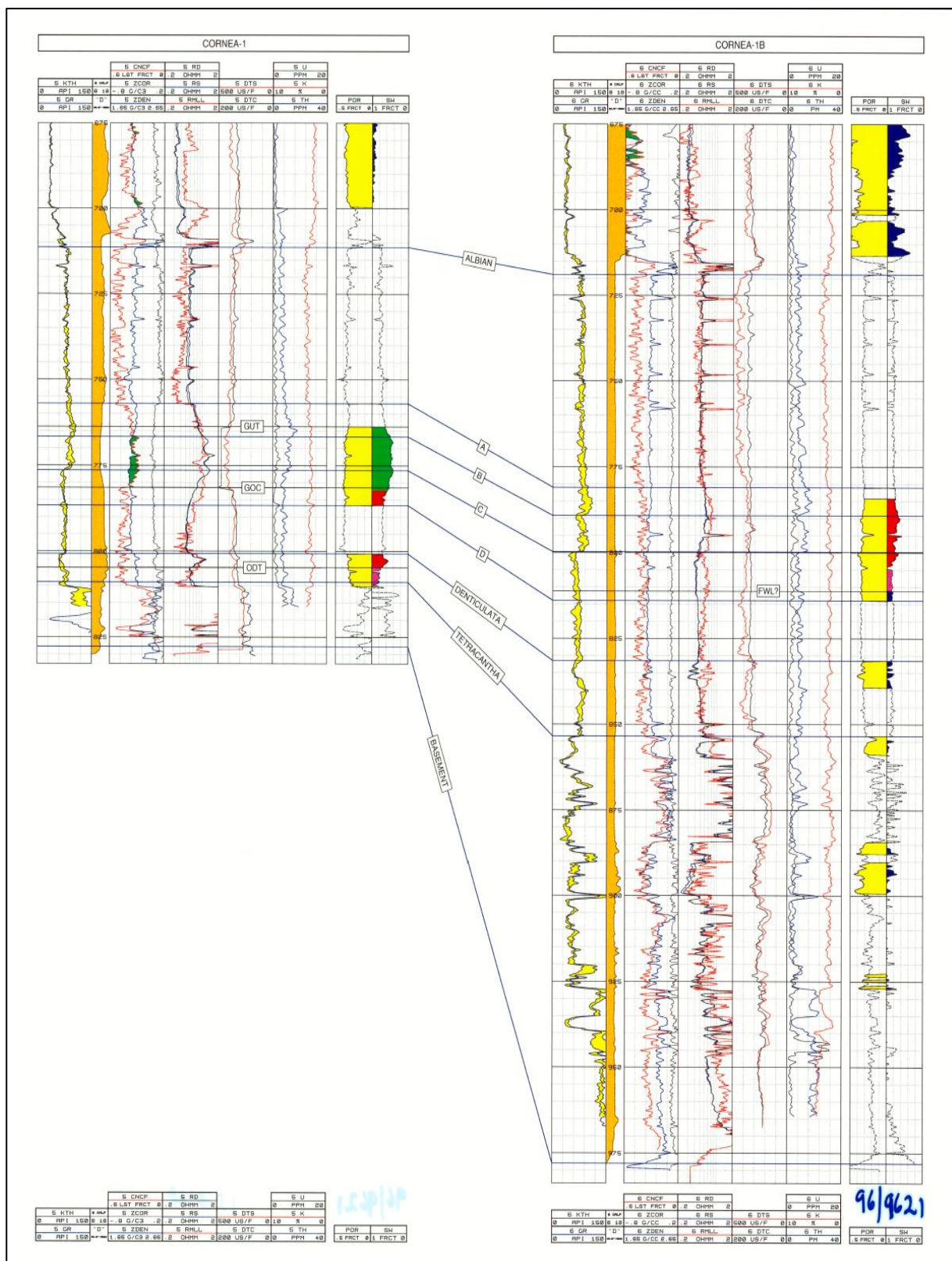


Figure 3.3: Cornea-1 and 1B well logs showing the five Albion units. © Commonwealth of Australia (Geoscience Australia) 2015. This product is released under the Creative Commons Attribution 4.0 International Licence. <http://creativecommons.org/licenses/by/4.0/>

3.2 The Cornea Field: Geophysical Background

The discovery well was drilled in 1997 based on a flatspot observed in 2D seismic data. The flatspot turned out to be an oil-gas contact at well Cornea-1. Later during the same year, 2100 square kilometres of 3D seismic data were acquired by SDA over the Cornea structure. The 3D data was reprocessed by Hawkstone in 2008. The reprocessing of the data resulted in multiple energy reduction. The 3D seismic data are of reasonable quality. The Pre-Aptian Basement can easily be mapped as it shows as a strong seismic trough event across the 3D data. It, however, steeply dips in strike and dip directions (Moby Oil and Gas Ltd, 2009).

3.3 The Cornea Field: Petrophysical Background

Several wells were drilled within or around the Cornea field since 1997. These wells include Cornea-1, Cornea-1A, Cornea-1B, Cornea-2, Cornea-3, Cornea South-1, Cornea South-2, Tear-1, Stirrup-1, Focus-1, Macula-1, Hammer-1, Sparkle-1, and Londonderry-1 (Figure 3.4). Wireline logs including Gamma Ray log, Porosity log, resistivity log and sonic log were collected from some of these wells. In addition, cores were cut in some of these wells (Geoscience Australia, 1997).

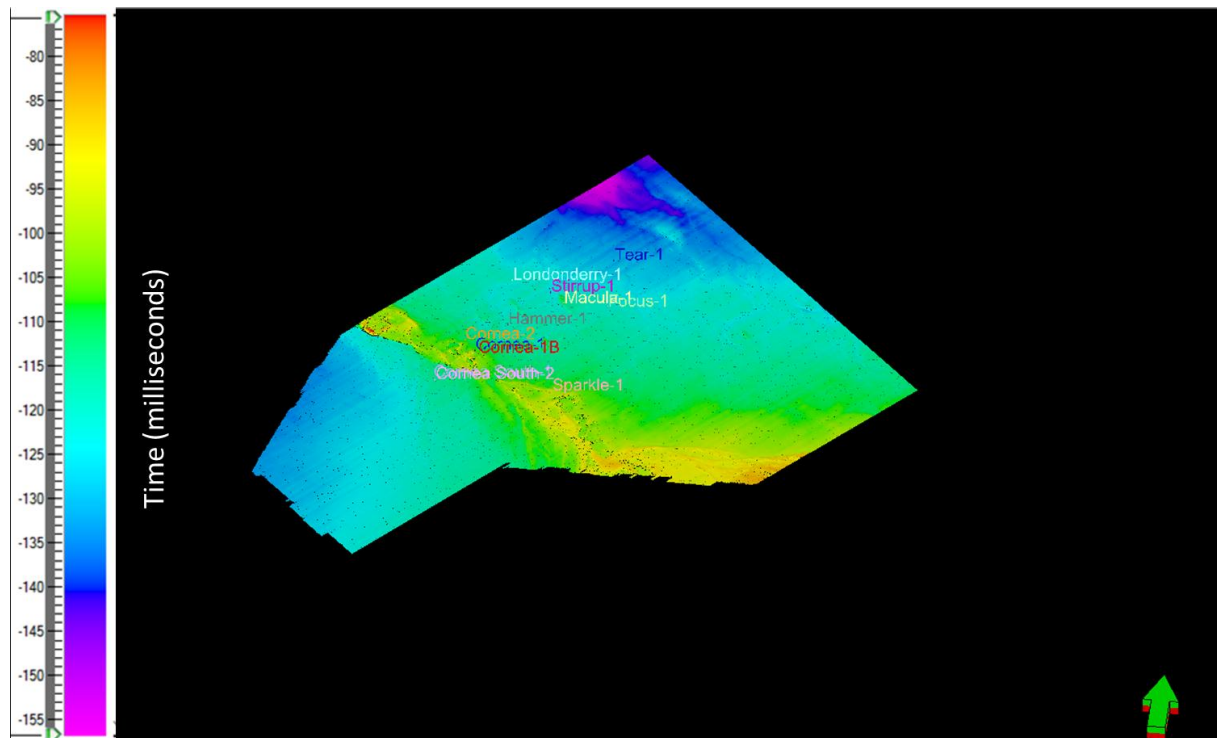


Figure 3.4: Wells within and around the Cornea field shown on the seabed time horizon.

Petrophysical data were mainly utilized for seismic interpretation i.e. time horizon picking of the Pre-Aptian Basement.

CHAPTER 4

SedSim STRATIGRAPHIC FORWARD MODELLING

Synopsis:

This chapter shows how SedSim stratigraphic forward modelling software was used. It explicitly shows the input and output to the software. In addition, it shows how the final results from SedSim were prepared for use in the VPC rock physics model.

4.1 SedSim Input

As mentioned previously, SedSim input can be divided into two types: SedSim parameters, which exist within the computational modules and can be user-modified, and additional input, which mainly comprises acquired data within the area of study (Griffiths & Paraschivoiu, 1998).

Within a SedSim input text file (Appendix E), each computational module is listed followed by its adjustable input parameters. Initially, most of these input parameters are set to default values. Some of the computational modules are initially “commented” or “turned off”. This means that they will not be utilized in the construction of the stratigraphic model. In this study, to generate a stratigraphic model over the specified area of the Cornea field, some SedSim computational modules were used while others were not utilized. The computational models utilized are:

TIME: the Time module contains three important parameters: The Simulation Interval (start and end times of simulation), the Display Interval and the Flow Sampling Interval. The Simulation Interval is specified in terms of geological time e.g. one million years ago (-1000000) and is dependent on the geological interval to be modelled. In this study, the interval to be modelled extends from pre-Albian basement level (> 113 million years ago) all the way to the seabed. The initial SedSim simulations ran from the Aptian seismic marker at 120 million years ago to the Turonian sediments (98 million years ago) which includes the Albian (113 Ma to 100.5 Ma) reservoir interval of interest in the ‘Upper Heywood Fm.’. The Display Interval determines interval in years at which the results files are

updated, while the Flow Sampling Interval determines the interval in years at which fluid elements are released from the river source. The smaller these numbers are the higher the time resolution of the simulation but the longer the computational time. These two parameters were initially set at 500000 and 100000 years, respectively, to give rapid results at a resolution greater than the number of seismic reflections observed in the section from Basement to surface (around 20). This gave 72 preserved layers at the location of Cornea-1.

GRID: The grid spacing for the generated Sedsim stratigraphic model determines the spatial resolution of the model. The stratigraphic model will be used to generate synthetic seismic, and the synthetic seismic data will, in turn, be compared to the observed Cornea 3D seismic data over the same area within the Cornea field. For the two seismic data sets, synthetic and observed, to be comparable, the grid spacing is chosen while taking into account the acquisition parameters and the resolution of the observed 3D seismic data. In particular, grid spacing is chosen based on the CDP spacing of the observed Cornea 3D seismic. Therefore, the regional grid spacing was initially set to 500 meters. Sedsim can also model a fine grid nested within the regional grid at a specified location. The resolution of this fine grid was set to 50 m.

SEDIMENTS: The Sediments routine allows the user to specify the input grain size, density and mode of transportation (suspension or bed-load) of sediments to be transported into the simulation area. Sedsim uses four clastic grain categories: Coarse, Medium, Fine and Finest. For each of these four categories, the user can specify a grain size in millimetres, the density in kilograms per cubic meters and choose whether the mode of transportation will be suspension or bed-load. The grain size for each category was chosen based on the Udden-Wentworth scale and the Cornea-1 cuttings description. The grain densities were taken from literature for the minerals recorded in the cuttings and core descriptions. The mode of transportation was assumed to be suspension.

POROSITY TABLE: The Sedsim input porosity table allows the user to specify how initial porosities for sediment of varying mixtures respond to burial pressure. The default porosity table in Sedsim input text file was used.

SOURCE: Source defines the flow parameters of sediment sources (usually rivers or beaches). These parameters include Source Location, flow height, Velocity at Source, Discharge Rate, Sediment Concentration and Sediment Composition. Six source points were specified in this study. Source 1 was located based on a previously published Sedsim study within the Browse basin. This source was located in the eastern part of the study area. Sources 2 through 6 were added based on Sedsim runs results. These were located in the eastern, southern, northern, western and eastern parts of the study area, respectively. The parameters of each source were modified also based on the run results throughout the study.

The depositional environment was considered when locating the sources. The initial source locations from 120 Ma to 112 Ma reflected the erosion of the Cornea high providing sediment laterally to the NW of Cornea and into the valley to the SE of the high (source 5), the more sand-rich sediment flowing NNE to SSW along the Cornea valley to the SE of the high (source 4) and sediment provided from the eastern coast-line across the coastal plain (source 6)

Sources 1 and 2 from 112 to 56 Ma (following the major transgression) were restricted to the eastern part of the simulation (entering the simulation area from the east with a lower sand content and higher flow rates from the continent. Source 3 reflected sediment from the SE flowing towards the Cornea area along the coastal margin through longshore currents into the “Tetracantha islands” area.

Based on information from the wells and regional studies we know the marine temperature conditions for carbonate deposition. Based on that information we know that after 56 Ma the deposition within the Cornea field is dominated by carbonates. Carbonates are never turned off in this Sedsim simulation but the temperature conditions for growth control their deposition.

PARAMETRIC SAMPLING INTERVAL: Parametric Sampling Interval is the time interval in years at which sea level curve, wave influence, compaction and other parameters are sampled or calculated. The smaller the Parametric Sampling Interval the higher the resolution of the model but the longer the computational time. The Parametric Sampling Interval was set to 100000 years to match the flow sampling interval.

SEDIMENT TRANSPORT PARAMETERS: Contains parameters that can better control the sediment transport process. These parameters are Maximum Depth of Fluid Elements, Minimum Velocity of Fluid Elements and Load at Source. Sedsim default values for these parameters were used.

SEA LEVEL: The 2012 Haq et al. eustatic sea level curve was used to provide accommodation control in addition to tectonic subsidence because the core data from the Cornea field indicated an open marine environment.

TECTONICS: Tectonic subsidence was controlled with the file “cornea_112-0Ma_linear_subsidence_36x68.tec” which allowed four discrete subsidence intervals, A. from 122 Ma to 72 Ma, (Albian to top Campanian) B. 72 Ma to 53 Ma, (Maastrichtian to Early Eocene) C. 53 Ma to 1 Ma (Tertiary carbonate regime), D. 1 Ma to present (sediment starved transgression).

Faults are simulated based on knowledge from literature and data using the TECTONICS module. In this study, the simulation was set to start from the Pre-Aptian Basement to sea level. We know from literature and simple interpretation of seismic data that faults die at the basement in the Cornea field. Therefore, no faults were simulated.

COMPACTION: Sedsim calculates compaction based on a table, which contains porosity (and thickness) reduction values as a function of burial stress (pressure in MPa) and grain sorting (Porosity Table in Appendix E). Consequently, compaction is controlled by pressure and grain size mixture for each display interval. Post-depositional compaction can be applied after simulation. Parameters within

the Compaction module including depth of post-depositional burial by sediment and water were estimated as 100 meters and 83 meters, respectively, based on Cornea field well reports.

The change of porosity with depth is included in all stages of the simulation, both during depositional loading and post-depositional burial. This effectively combines the processes that influence mass volume reduction and porosity/permeability reduction with both elapsed time and depth. The final porosity volume reduction with depth table used in this study can be found in POROSITY TABLE in the Sedsim input file (Appendix E). The columns represent the effect of burial pressure from zero to 50 MPa on the porosity and volume reduction for ratios of clay to sand of zero to unity. This table can be compiled from published or proprietary studies and/or calibrated against available well data (core and/or wireline). In this study, initially, the default one was used and the final one was determined during Sedsim runs.

The porosity reduction will usually be a combination of compaction and diagenesis. Porosity enhancement can also include sub-seismic fracture effects as well as diagenesis. In Sedsim, for specific locations, such effects can be included both by using the POROSITY routine above and within the CARBONATES AND ORGANICS module where diagenesis can affect porosity in clastics and carbonates without rock volume changes as a function of elapsed time in years.

Other Sedsim input consisted of the initial bathymetric/topographic surface. This was a seismic time surface representing the Pre-Aptian Basement. It was picked on the observed Cornea 3D seismic data as a strong trough seismic event (Figure 4.1). The Pre-Aptian Basement surface resolution was modified using the 'Transform' program in order to be able to use it within Sedsim. No other data were used as input for this study.

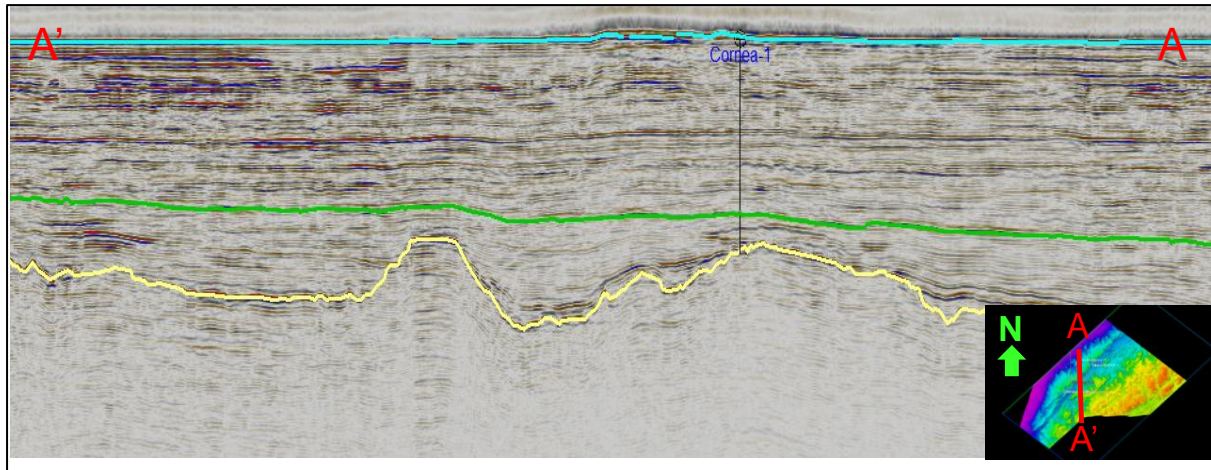


Figure 4.1: A south-north line through Cornea observed 3D seismic data. The line shows the Pre-Aptian Basement (yellow), the Turonian unconformity (green) and seabed (blue). The Pre-Aptian Basement was picked as a 3D time horizon (corner).

4.2 Sedsim Runs

It took approximately thirty runs until a reasonable Sedsim stratigraphic model was finally generated. The results of each run guided the decision of which parameters to be modified. Initially as the results were clearly unreasonable, the parameters were adjusted without going through the process of closing the loop. The process of closing the loop was utilized when the results became more reasonable i.e. as errors became harder to spot.

The thirty Sedsim runs are summarized in four batches as follows:

Sedsim Runs 1-2: A Pre-Aptian Basement bathymetry surface covering the whole study area (brown) was used. Source 1 was added. Major areas were not covered by sediment flow: a problem of non-deposition (Figure 4.2).

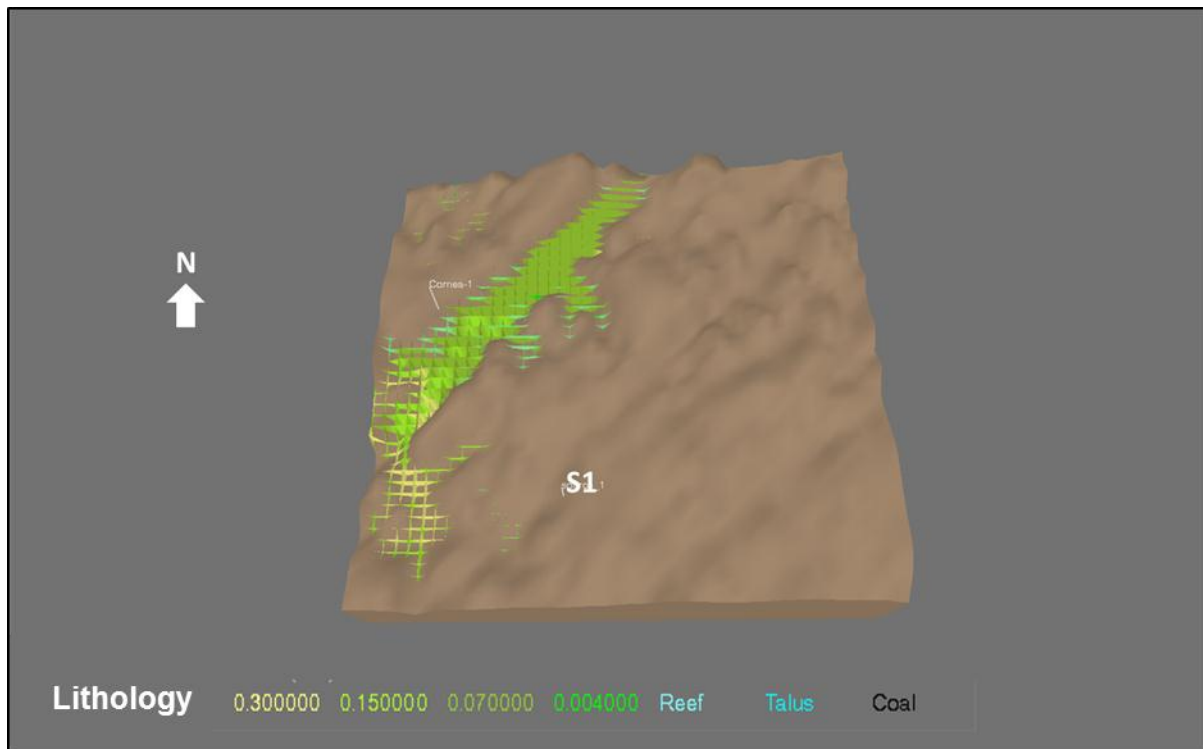


Figure 3.2: Top view of Sedsim stratigraphic model from Run 2 showing the location of Source 1 (S1). Sediments were deposited in the western part of the study area on the Pre-Aptian Basement bathymetry surface (brown surface) whereas the rest of the area remained without deposition.

Sedsim Runs 3-9: Two more sources were added, Source 2 and Source 3 in the central and western parts of the study area, respectively, while Source 1 was move to the west. Adding these sources partially solved the problem of non-deposition (Figure 4.3).

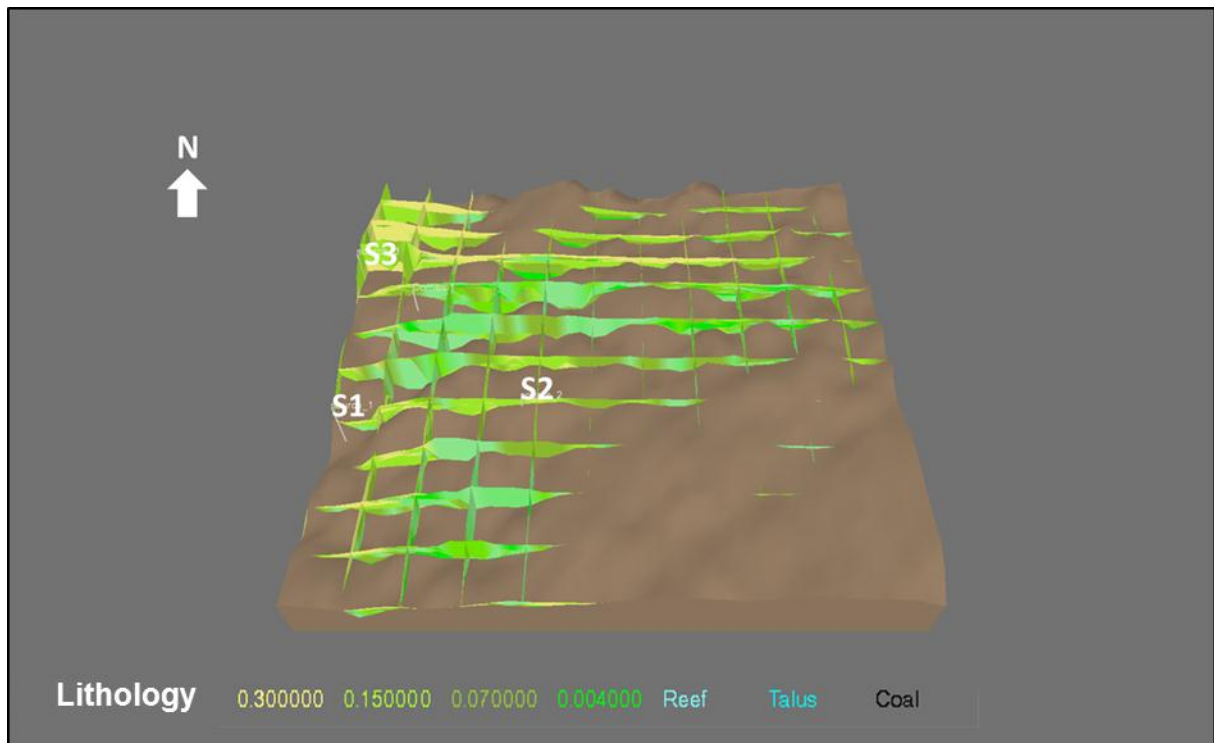


Figure 4.3: Top view of Sedsim stratigraphic model from Run 9 showing the new location of Source 1 (S1) and the location of Sources 2 (S2) and 3 (S3). The addition of Sources 2 and 3 expanded the area of sediment deposition. The southwestern part of the study area remained without deposition.

Sedsim Runs 10-16: Waves module was turned on. The problem of non-deposition was solved but there was an interval where sediments were deposited abruptly resulting in the formation of one thick layer. Based on an initial closing-the-loop run, this was not supposed to be the case; finer layers within that thick layer should have been deposited (Figure 4.4 & Figure 4.5).

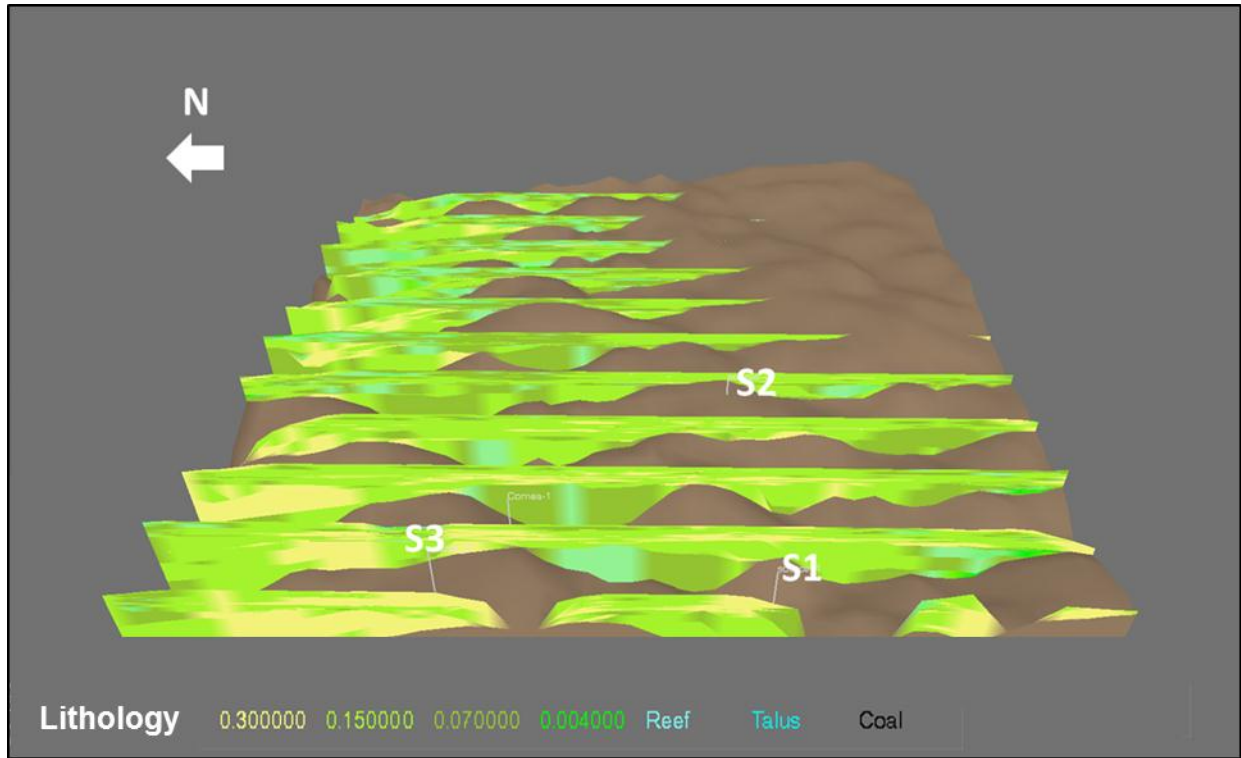


Figure 4.4: Lines through Sedsim stratigraphic model from Run 16 in terms of lithology.

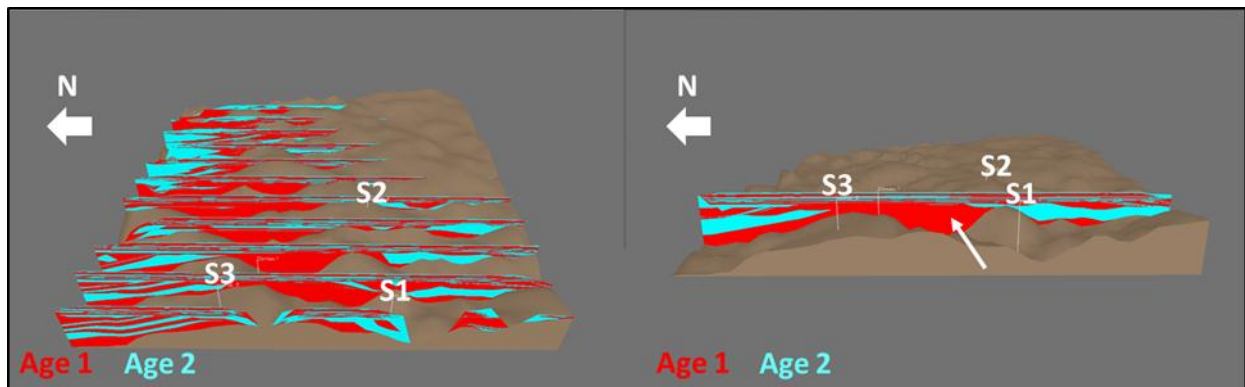


Figure 4.5: Left: lines through stratigraphic model from Sedsim Run 16 in terms of alternating age. Right: a single line through the same run showing a thick layer, which was deposited abruptly (pointed by white arrow). The line was converted to synthetic seismic and compared to its corresponding observed seismic line. The comparison showed that thin layers were supposed to be deposited within the thick layer.

Sedsim Run 17-31: Three more sources were added. These were Sources 4, 5 and 6 in the northern, western and eastern parts of the study area, respectively. This run was set to start from the Pre-Aptian Basement all the way to seabed. In addition, the locations of Sources 1, 2 and 3 were modified. The

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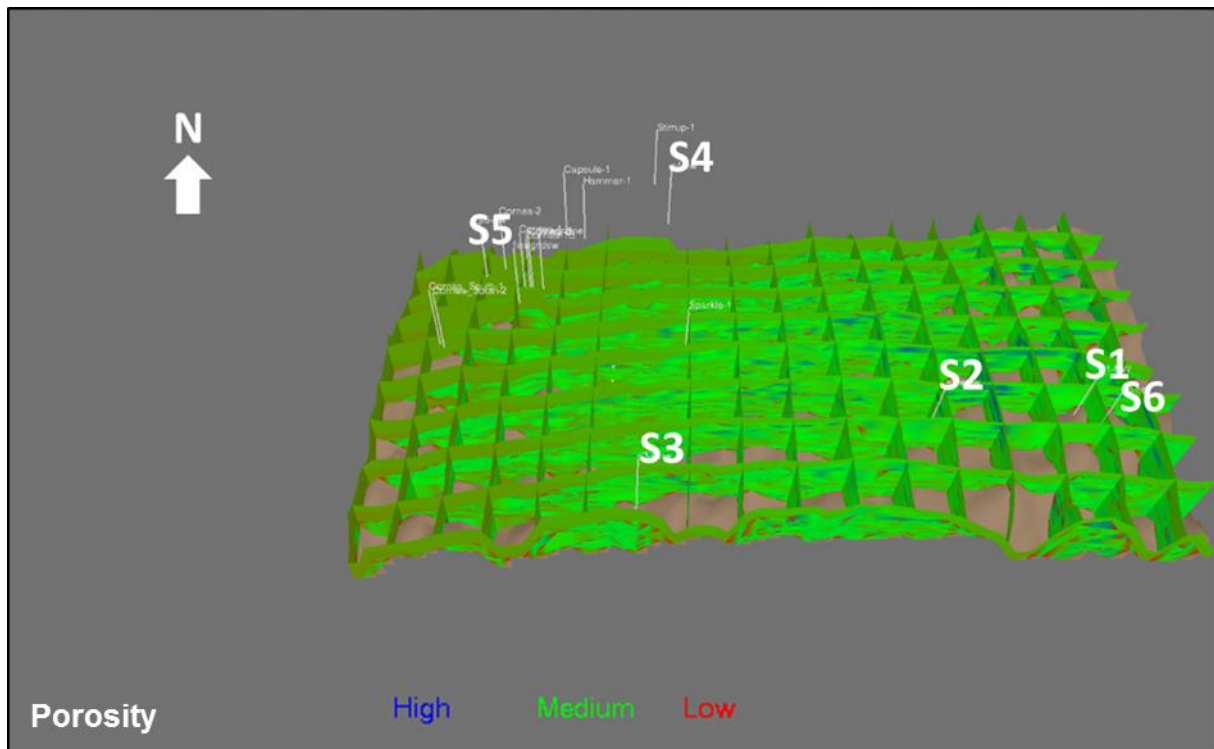


Figure 4.7: Final Sedsim stratigraphic model (Run 31) in terms of porosity. Note that blue, green and red are high, medium and low porosity, respectively.

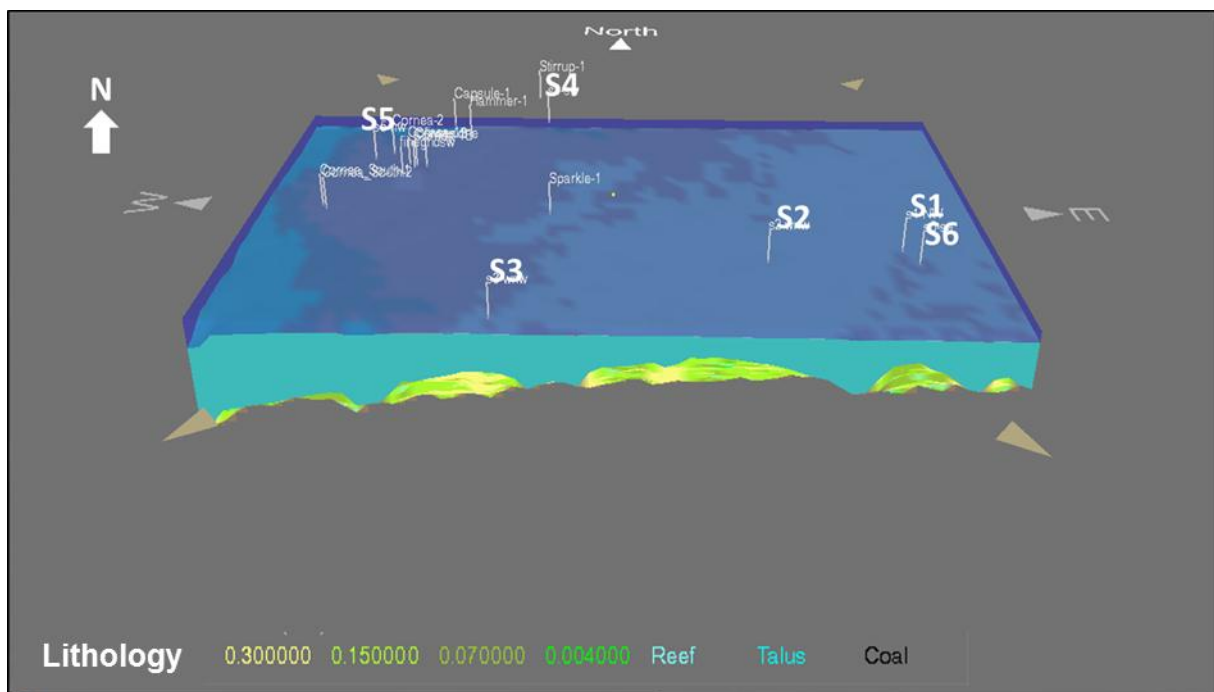


Figure 4.8: Top view of Sedsim stratigraphic model from Run 31 showing the final locations of all six sources. The run was set from the Pre-Aptian Basement all the way to seabed depositing both the siliciclastics interval and the carbonate-dominant interval.

The above summary highlights important changes that were made during the runs. For more details including all changes made during each run see the top part of the input text file (Appendix E). In addition, note that run 11 was utilized for testing purposes and therefore was not included in the text file.

4.3 Sedsim Output Parameters

Sedsim divides the stratigraphic model into a number of nodes. On a horizontal “slice” of the stratigraphic model, each node can be thought of as a point. On a vertical line passing through a node, the node looks like a well-log starting from the shallowest depth of the stratigraphic model and ending at the bottom depth of the model. The vertical line of the node is divided into intervals of depth or “blocks”, which are generated at preserved geological time intervals. For example, although a new depth interval can be created every ten thousand years not all of the time intervals have sediment deposited at that time at that location, or not eroded later. The number of nodes, the distances between them and the geological time interval are user-specified (Figure 4.9).

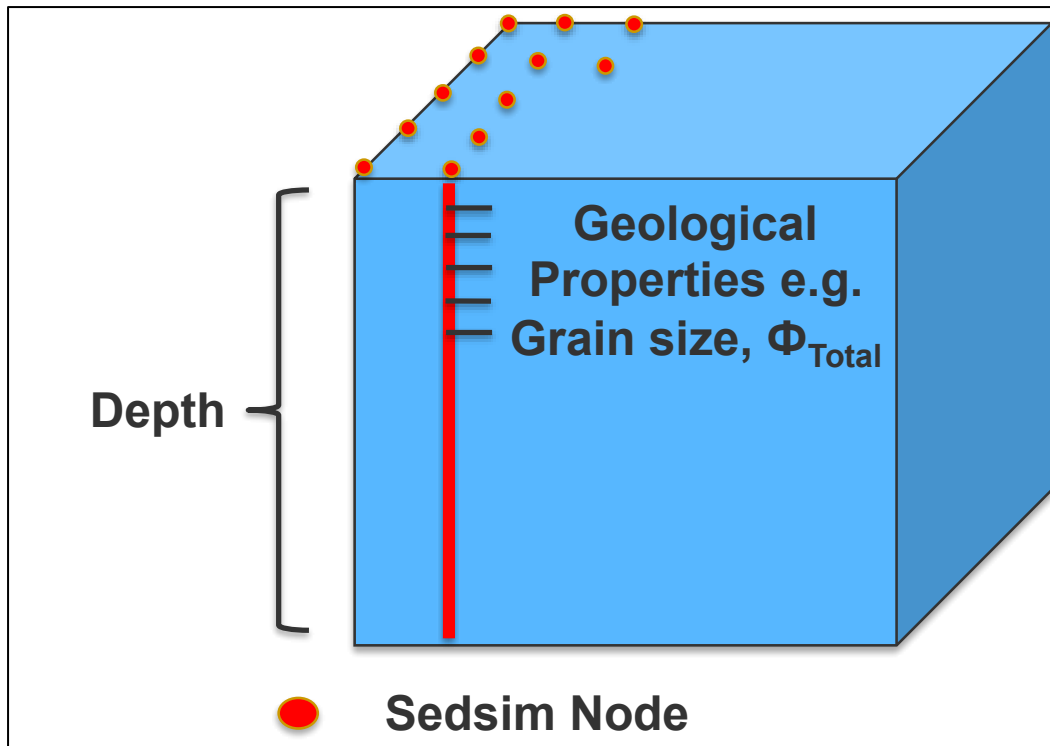


Figure 4.9: Illustration of Sedsim nodes: Sedsim stores output in a series of nodes (red circles). Each node can be thought of as a vertical log (red line), which contains geological properties at each depth interval (marked by the black ticks).

Each node contains quantitative information on the geological properties of the stratigraphic model at the node location. Sedsim output is represented as a text file containing information in a tabular format. A simple example of one node from a simulation is shown in Appendix F. The file may contain information relating to one or more nodes as required. The information includes:

- The location of the node in terms of column and row as well as X_{utm} and Y_{utm} coordinates.
- The elapsed time interval for each depth interval or block.
- The geological time of each depth interval or block.
- The length of each depth interval or block.
- The component proportion of each grain size gr within each depth interval/block. These are: $(gr_1(m))$, $(gr_2(m))$, $(gr_3(m))$, $(gr_4(m))$, $(gr_5(m))$, $(gr_6(m))$, $(gr_7(m))$ and $(gr_8(m))$ (Table 4.1).

- The porosity within each depth interval/block.
- The top depth of each depth interval/block.
- The bottom depth of each depth interval/block.

The number and the location of nodes to be output in the text file can be specified in Sedsim.

Grain	Size (millimeters)	Lithology	Mineral
gr1	0.3	Coarse sandstone	Quartz
gr2	0.15	Medium sandstone	Quartz
gr3	0.07	Fine to very fine sandstone	Quartz
gr4	0.004	Very fine clay	Clay
gr5		Carbonate	Calcite
gr6		Carbonate	Calcite
gr7		Organic Matter	Calcite
gr8		Organic Matter	Calcite

Table 1.1: Summary of size, lithology and mineral each grain size within Sedsim represents.

4.4 Preparing Sedsim Output for The VPC Rock Physics Model

Sedsim gives two main initial input parameters required by the VPC rock physics model (Goldberg & Gurevich, 1998). One of them is the porosity within each depth interval. This parameter is given directly. The other parameter, the volume fraction of the constituent minerals within each depth interval, however, is not given directly and is calculated. Instead of giving the volume fraction of each mineral, Sedsim gives thickness of each grain size ($gr1(m)$ to $gr8(m)$) within each depth interval. As shown in Table 4.1, a grain size or a group of grain sizes represent certain lithology. For example, the group $gr1(m)$, $gr2(m)$ and $gr3(m)$ represent thickness of different sizes of sandstones. In this study, we assume that each lithology type corresponds to one mineral e.g. sandstones correspond to quartz. This information can be used in order to calculate constituent minerals volume fractions of each mineral at each depth interval as follows:

The fraction value for each grain size is calculated. This is done by calculating the sum of all grain size thicknesses $gr1$ (m) to $gr8$ (m) for a depth interval. Then, dividing grain size thickness for which grain size fraction is to be calculated, by the calculated sum. For example, in order to determine the grain size fraction $gf1$ for grain size $gr1$, all grain size thicknesses from $gr1$ to $gr8$ are summed. Then, $gf1$ is calculated by dividing grain size thickness $gr1$ by the calculated sum:

$$gf1 = \frac{gr1}{gr1 + gr2 + gr3 + gr4 + gr5 + gr6 + gr7 + gr8} \quad (13)$$

, where $gf1$ is the grain size fraction of grain size 1 and $gr1$ to $gr8$ are grain sizes 1 to 8.

The same process is repeated for the rest of the grain sizes to calculate grain size fractions for the remaining grain sizes. The general form of equation (13) is:

$$gfx = \frac{grx}{gr1 + gr2 + gr3 + gr4 + gr5 + gr6 + gr7 + gr8} \quad (14)$$

, where x is an integer ranging from one to eight, gfx is the grain size fraction of grain size x , grx is the grain size of x and $gr1$ to $gr8$ are grain sizes 1 to 8.

Sandstone fraction SF is calculated for each depth interval. Out of the grain sizes thicknesses $gr1$ to $gr8$, only $gr1$, $gr2$ and $gr3$ represent Sandstone grains thickness. Therefore, when it comes to calculating sandstone fraction SF, only $gr1$, $gr2$ and $gr3$ will be used. In this Sedsim simulation $gr1$, $gr2$ and $gr3$ are assigned grain sizes 0.3 mm, 0.15 mm and 0.07 mm, respectively. Based on Udden-Wentworth scale, $gr1$, $gr2$ and $gr3$ are classified as coarse sand, medium sand and fine to very fine sand, respectively. The sum of their corresponding grain size fractions, $gf1$, $gf2$ and $gf3$, is equivalent to the Sandstone fraction SF for each depth interval:

$$SF = gf1 + gf2 + gf3 \quad (15)$$

, where SF is the sandstone fraction and $gf1$ to $gf3$ are grain size fractions of grain sizes 1 to 3.

In this Sedsim simulation $gr4$ is given the grain size of 0.004 mm within Sedsim. Using Udden-Wentworth scale, this grain size is considered very fine clay (Mavko, Mukerji & Dvorkin, 2009). Therefore, $gf4$, the grain size fraction of $gr4$, is equivalent to the clay fraction for each depth interval. Hence, in order to determine the clay content C as a fraction, I simply assign the value of $gf4$ to the value of C for each depth interval:

$$C = gf4 \quad (16)$$

, where C is clay content and $gf4$ is grain size fraction of grain size 4.

The carbonate fraction CF is calculated using grain size thickness $gr5$ (m) and $gr6$ (m):

$$CF = gf5 + gf6 \quad (17)$$

, where CF is the carbonate fraction and $gf5$ and 6 are the grain size fractions for grain sizes 5 and 6.

Finally, organic matter fraction OF is calculated using grain size thickness $gr7$ (m) and $gr8$ (m):

$$OF = gf7 + gf8 \quad (18)$$

, where OF is organic matter fraction and $gf7$ and 8 are the grain size fractions for grain sizes 7 and 8.

Sandstone fraction SF , Clay Content C , carbonate fraction CF , organic matter fraction OF and total Porosity calculated from or given by Sedsim stratigraphic model will be used as initial input for the rock physics model.

CHAPTER 5

VELOCITY-POROSITY-CLAY (VPC) ROCK PHYSICS MODEL

Synopsis

This chapter gives an overview of the compatibility of the VPC rock physics model to the study area and SedSim. It also shows the input and output of the VPC rock physics model.

5.1 VPC Compatibility to Study Area

The Albian sands within the Cornea field range from siltstones to sandstones. The main target in this study is the Albian sandstones. These form isolated bodies of sandstone in the middle of siltstone and clay-rich sediments (Geoscience Australia, 1997). Therefore, the following geological scenarios are possible within the Albian sands: clay, clay-rich sandstones and clean sandstones.

The bulk modulus of the solid grains, $K_{effective}$, is calculated in the VPC model using the lower Hashin-Shtrikman bound. The choice of the lower bound corresponds to geometrical configurations where clay is the primary load-bearing material. Thus, the VPC model is compatible with the clay case (Goldberg & Gurevich, 1998).

In the case of relatively low-clay content, the Hashin-Shtrikman upper and lower bounds are close to each other. Therefore, the choice of the lower bound as opposed to the upper bound does not matter and the VPC model can still be used for relatively low-clay content or clean sandstones (Goldberg & Gurevich, 1998).

The VPC model was initially designed as an extension of the Krief et al. Velocity-Porosity model to enable the use of the Velocity-Porosity model in the case of clay-rich sands, including clay-rich sandstones (Goldberg & Gurevich, 1998). Therefore, the VPC model is compatible with clay-rich sandstones.

Based on the above, the VPC model is compatible within the Albian sands, the main target of the study area. However, the VPC model is utilized in the whole study area including areas and formations outside the Albian sands.

The lithology within the study area can generally be divided into two intervals (Figure 5.1): siliciclastic lithology between the Pre-Aptian Basement and Turonian Unconformity and carbonate-dominant interval above the Turonian Unconformity (Geoscience Australia, 1997). The VPC is compatible with the siliciclastic interval, which include the Albian sands. However, when it comes to the carbonate-dominant interval, the VPC may or may not be compatible.

It is worth mentioning that the Krief model, from which the VPC model was derived, is affected by depositional processes. Since, in this study, the exact process of deposition is defined in Sedsim, a model that is completely adequate to this process can be defined. This is in contrast to usual seismic inversion where general model that works for a range of formations is needed. Defining a range of models for each process, while feasible, requires further research and is beyond the scope of this study.











Targets	Actual				Tops	TWT
	Lithology	Formation	Stage	Period	mRT (mSS)	
		 Seabed			105	
	Not Sampled - Returns to seabed	Undifferentiated	Undifferentiated	Undifferentiated Tertiary to Recent		
		Hibernia / Bathurst Island	Paleocene to Maastrichtian		645	
		Upper Heywood Fm	Cenomanian		711.3	621
		Layer A	Albian	Cretaceous	757.0	663
		Layer B			766.6	675
		Layer C			776.4	686
		Layer D			786.6	692
		Denticulate Sst			800.7	711
		Tetracantha Sst				
		Basement	Proterozoic		827.8	730
					831	

Figure 5.1: Cornea-1 stratigraphy showing siliciclastics from Basement to the Turonian Unconformity and carbonates above the Turonian unconformity. © Commonwealth of Australia (Geoscience Australia) 2015. This product is released under the Creative Commons Attribution 4.0 International Licence. <http://creativecommons.org/licenses/by/4.0/>

Although ideally, a different rock physics model should be utilized for the carbonate-dominant interval, in this study, the VPC is applied to the whole Sedsim model including the carbonate-dominant interval (Figure 5.2).

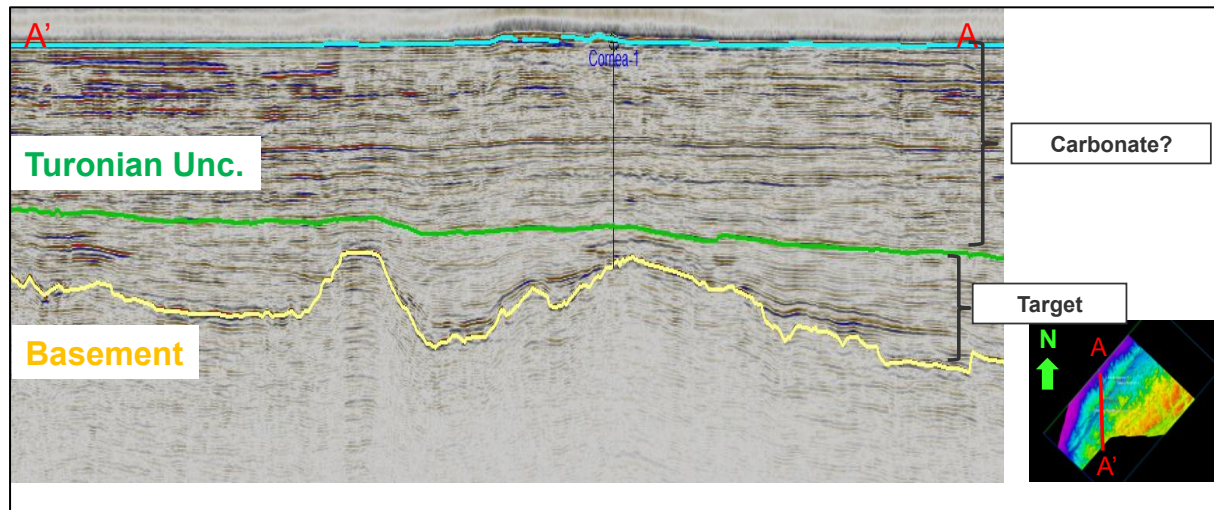


Figure 5.2: A south-north line through Cornea observed 3D seismic data. The Velocity-Porosity-Clay (VPC) rock physics model is compatible within the target area between the Pre-Aptian Basement (yellow) and the Turonian Unconformity (green). However, VPC compatibility within the carbonate-dominant interval between the Turonian Unconformity and seabed (blue) is questionable.

5.2 VPC Compatibility to Sedsim Model

The compatibility of the VPC rock physics model to the Sedsim model is defined here as the ability to use certain output properties or parameters from the Sedsim model in order to prepare the necessary input for the VPC rock physics model.

The VPC model requires two initial input parameters. These are porosity and clay content. The Sedsim model provides the porosity for each depth interval or block in the model. As for the clay content, it can be calculated from grain size information provided by Sedsim for each depth interval or block.

5.3 VPC Input Parameters

For a given porosity and clay content, the VPC model requires a set of input parameters. In general, some of these parameters such as ρ_{sand} , ρ_{clay} , K_{fluid} are given accurately from literature, some such as K_{sand} and μ_{sand} are estimated from available acquired data and some parameters such as K_{clay} , μ_{clay} , and the constants A_0 and A_1 are, as mentioned previously, determined using a calibration procedure, namely, a two-dimensional non-linear regression fit (Goldberg & Gurevich, 1998).

In this study, since a Sedsim stratigraphic model is utilized, there is no need to use acquired data. Porosity and clay content are given by Sedsim. In addition, rather than going through the calibration procedure using data, constants A_0 and A_1 are assumed to be 4 and 0, respectively (Gurevich, 2015). The rest of the parameters are determined from literature (Mavko, Mukerji & Dvorkin, 2009) (Table 5.1).

Mineral	Bulk Modulus (GPa)	Shear Modulus (GPa)	Density (Kg/m ³)
Quartz	37	44	2650
Calcite	76.8	32	2710
Clay	21	7	2550

Table 2.1: Bulk and shear moduli and density values used in this study.

In equations (9) and (10) (Chapter 2, 2.11), $K_{effective}$ and $\mu_{effective}$ were written for a mixture of only two elements, sandstone and clay. In this study there are four possible elements. These are sandstone, clay, limestone and calcite-based organic matter. Therefore, equations (9) and (10) were

rewritten using the general Hashin-Shtrikman-Walpole lower bound to accommodate all four elements (Mavko, Mukerji & Dvorkin, 2009):

$$K_{effective} = \left(\left(\frac{SF}{K_{sand} + \Psi} \right) + \left(\frac{C}{K_{clay} + \Psi} \right) + \left(\frac{CF}{K_{calcite} + \Psi} \right) + \left(\frac{OF}{K_{calcite} + \Psi} \right) \right)^{-1} - \Psi \quad (19)$$

$$\mu_{effective} = \left(\left(\frac{SF}{\mu_{sand} + \xi} \right) + \left(\frac{C}{\mu_{clay} + \xi} \right) + \left(\frac{CF}{\mu_{calcite} + \xi} \right) + \left(\frac{OF}{\mu_{calcite} + \xi} \right) \right)^{-1} - \Psi \quad (20)$$

$$\Psi = \frac{4}{3} \mu_{min} \quad (21)$$

$$\xi = \frac{\mu_{min}}{6} \left(\frac{9K_{min} + 8\mu_{min}}{K_{min} + 2\mu_{min}} \right) \quad (22)$$

, where $K_{effective}$ and $\mu_{effective}$ are the effective bulk and shear moduli of the mixture, respectively, K_{sand} , K_{clay} and $K_{calcite}$ are the bulk moduli of sand, clay and calcite, respectively, μ_{sand} , μ_{clay} and $\mu_{calcite}$ are the shear moduli of sand, clay and calcite, respectively, SF , C , CF and OF are the sandstone fraction, clay content, carbonate fraction and organic matter fraction, respectively, K_{min} and μ_{min} are the minimum bulk and shear moduli, respectively.

5.4 VPC Output Parameters

The VPC rock physics model yields K_{dry} and μ_{dry} , the bulk and shear moduli of the dry solid matrix. These can then be inputted into Gassmann's equations to calculate K_{sat} and μ_{sat} , the bulk and shear moduli of the saturated rock (Figure 5.3) (Goldberg & Gurevich, 1998):

$$K_{sat} = K_{dry} + B^2 M \quad (23)$$

$$\mu_{sat} = \mu_{dry} \quad (24)$$

, where K_{dry} and K_{sat} are the bulk moduli of the dry and saturated rocks, respectively, μ_{dry} and μ_{sat} are the shear moduli of the dry and saturated rocks, respectively, B is the Biot compliance coefficient and M is the pore-space modulus.

It is important to point out that Gassmann's equations in this study are used to fill all existing porosity, total porosity, with water. Therefore, total porosity is used in these equations. No fluid substitution is made from water to hydrocarbon or vice versa where effective porosity should be used (Chapter 8, 8.4).

The bulk density of the saturated rock is calculated using the equation:

$$\rho_{sat} = \rho_{effective} (1 - \Phi_{total}) + \rho_{water} \Phi_{total} \quad (25)$$

, where ρ_{sat} is the density of the saturated rock, $\rho_{effective}$ is the density of the rock mixture, ρ_{water} is the density of water and Φ_{total} is the total porosity.

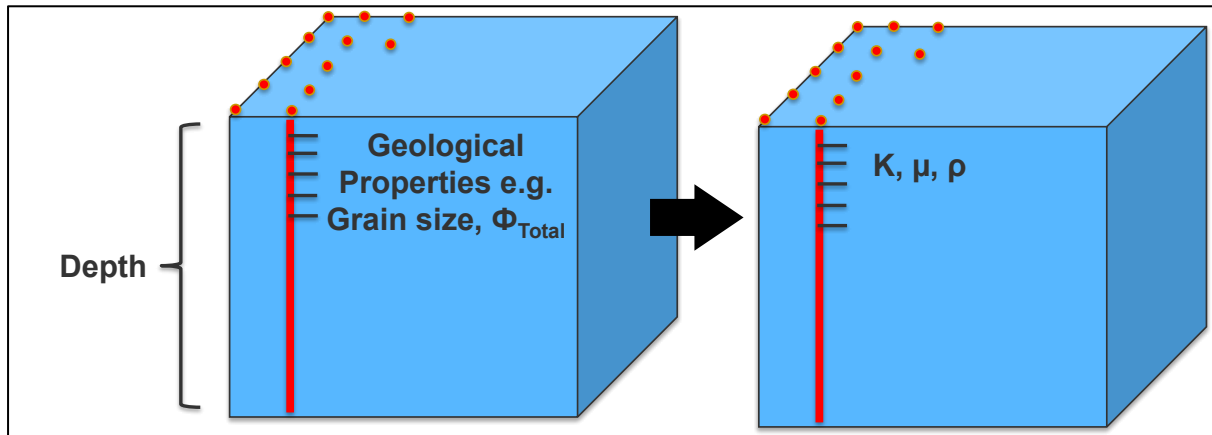


Figure 5.3: Grain size and total porosity from Sedsim at each depth interval (separated by black ticks) are used as input for the Velocity-Porosity-Clay (VPC) rock physics model. The VPC model, then outputs bulk and shear moduli at each depth interval in addition to density.

Finally, standard compressional and shear velocities formulae are used to calculate compressional and shear wave velocities (Figure 5.4):

$$V_p = \sqrt{\frac{K_{sat} + \frac{4}{3}\mu_{sat}}{\rho_{sat}}} \quad (26)$$

$$V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \quad (27)$$

, where V_p and V_s are the compressional and shear wave velocities respectively, K_{sat} and μ_{sat} are the saturated bulk and shear moduli and ρ_{sat} is the saturated rock density.

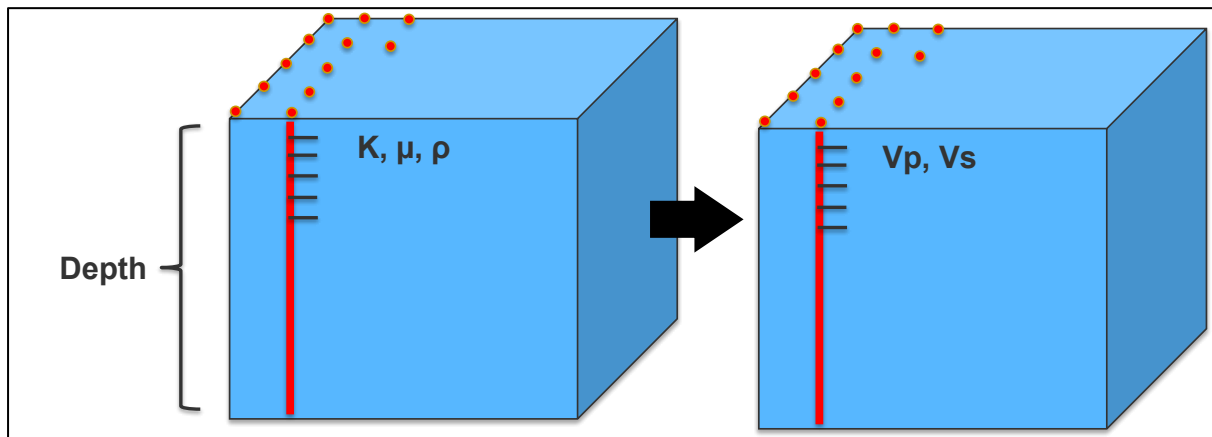


Figure 5.4: Bulk modulus, shear modulus and density at each depth interval (represented by black ticks) are used to calculate compressional and shear velocities at each depth interval.

CHAPTER 6

SEISMIC FORWARD MODELLING

Synopsis

This chapter explains how the output from the VPC rock physics model was converted to synthetic seismic data.

6.1 Calculating Acoustic Parameters

The main objective of this study is to generate a synthetic seismic volume comparable to the observed one over the Cornea field. As discussed earlier, in order to generate a synthetic seismic trace across a boundary between two geological layers, seismic velocities within each of these layers need to be known.

In this study, velocity within each layer is calculated using the output of the VPC rock physics model. As shown in the previous section, the VPC rock physics model yielded the elastic moduli and density values necessary to calculate compressional and shear wave velocities. The velocities are calculated for each Sedsim “block” at each Sedsim vertical node using standard velocities formulae.

Once the compressional and shear wave velocities are calculated for each Sedsim block, compressional and shear acoustic impedances at each boundary separating two blocks are calculated (Figure 6.1).

$$AI = V_p \rho_{sat} \quad (28)$$

$$SI = V_s \rho_{sat} \quad (29)$$

, where AI and SI represent acoustic and shear impedance, respectively, V_p and V_s are the compressional and shear wave velocities, respectively, and ρ_{sat} is the density of the saturated rock.

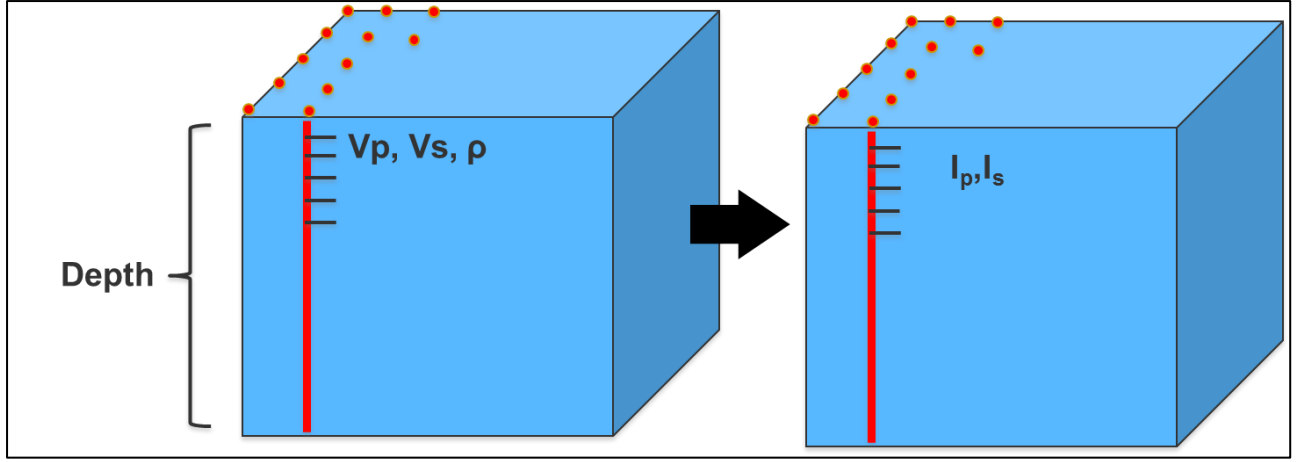


Figure 6.1: Acoustic and shear impedance are calculated at each depth interval (represented by black ticks) using calculated compressional velocities, shear velocities and densities.

Before reflection coefficients at each boundary are calculated, the two-way travel time to the boundary is calculated in two steps: first, the interval two-way travel time from the top of a Sedsim block the bottom of the block is calculated using the calculated velocity within the block and the depth from the top of the block to the bottom of the block. The depth is calculated by taking the difference between the depth at the bottom of the block and the depth at the top of the block, which are given by Sedsim. This is repeated for all Sedsim blocks. Second, the cumulative two-way travel time to each boundary separating two blocks is calculated:

$$tw_{t_{interval}} = 2 \left(\frac{d_z}{V_p} \right) \quad (30)$$

$$tw_{t_{cumulative_i}} = tw_{t_{interval_i}} + tw_{t_{interval_{i-1}}} \quad (31)$$

, where $tw_{t_{interval}}$ and $tw_{t_{cumulative}}$ are the interval and the cumulative two-way times, respectively, d_z is the interval depth, V_p is the compressional wave velocity of the interval and i is a counter.

Next, reflection coefficients at each boundary are calculated:

$$R = \frac{AI_2 - AI_1}{AI_2 + AI_1} \quad (32)$$

, where R is the reflection coefficient and AI is the compressional acoustic impedance (1 is above the boundary and 2 is below the boundary).

So far reflection coefficients have been calculated at each boundary. In order to generate synthetic seismic a reflectivity function must be generated using these reflection coefficients. This function is then convolved with a wavelet to generate synthetic seismic:

$$S(t) = w(t) * R(t) \quad (33)$$

, where $S(t)$ is seismic, $w(t)$ is a wavelet and $R(t)$ is reflectivity all as functions of time t and $*$ denotes convolution.

In this study the convolution was performed in the frequency domain i.e. the wavelet and the reflectivity function were transformed to the frequency domain using Fourier transformation:

$$S(f) = w(f)R(f) \quad (34)$$

, where $S(f)$ is seismic, $w(f)$ is a wavelet and $R(f)$ is reflectivity all as functions of frequency f .

By transforming the wavelet and the reflectivity function to the frequency domain, synthetic seismic can be generated by multiplying the two functions instead of convolving them. In addition, generating the reflectivity function and its transformation to the frequency domain are achieved in one step:

$$R_{fft} = R_{fft} + R(k)e^{-i \omega t w t c(k)} \quad (35)$$

, where R_{fft} is Forward Fourier Transform of the reflection coefficients, R is reflection coefficient, ω is the angular frequency, $twtc$ is the cumulative two-way time, k is a counter and i is the square root of negative one.

The wavelet chosen in this study is Ricker wavelet (Figure 6.2), since it is a common source wavelet. It is transformed to the frequency domain via the Fourier transformation. After both the reflectivity function and the Ricker wavelet are transformed to the frequency domain, they are multiplied and the result is the seismic trace in the frequency domain.

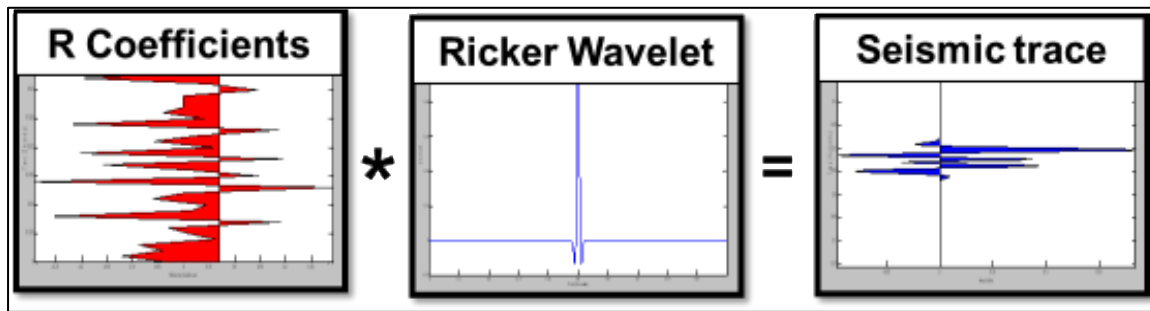


Figure 6.2: Applying the convolutional model at one Sedsim node to generate a seismic trace. Reflection coefficients are calculated and convolved with a Ricker wavelet (middle) in the frequency domain to generate seismic data. Note: Star denotes convolution.

The seismic trace is then transformed from the frequency domain to the time domain using the inverse Fourier transform. The final result is a synthetic seismic trace at a Sedsim node location. Initially the process was repeated at nodes sharing the same X-UTM coordinate but different Y-UTM coordinates to generate a synthetic seismic line. Then, the process was repeated for all Sedsim nodes to generate a synthetic seismic volume. The observed seismic acquisition parameters were taken into account when the parameters of Sedsim stratigraphic model were set (Figure 6.3).

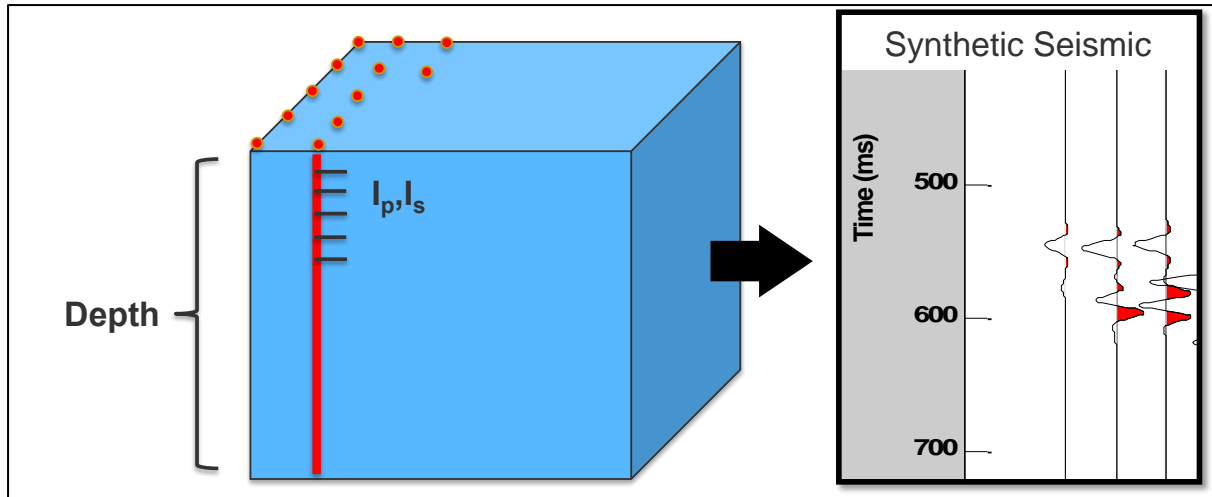


Figure 6.3: Reflection coefficients are calculated at each Sedsim node (red circle) using the calculated compressional impedance. Then, a synthetic seismic trace is generated at each Sedsim node.

The whole process starting from using Sedsim output as input into the VPC rock physics model to generating the synthetic seismic volume was coded in MATLAB (Appendix A-D). The VPC rock physics model portion of the code was a modification of a previously written VPC code (Al-Siyabi, 2012). CREWES code was used to transform the seismic data to SEG Y format.

6.2 Synthetic Seismic data display method

Since the synthetic seismic data was generated using MATLAB, it was also displayed in MATLAB using MATLAB Plot function. This worked well when the generated synthetic seismic to be displayed consisted of one seismic trace or a part of a seismic line. As the number of traces increased to generate a longer seismic lines or volumes, another display method capable of handling large number of traces was needed.

A CREWES code capable of exporting seismic data in SEG Y format was utilized. The SEG Y synthetic seismic data were then loaded in Petrel, the same software used to display the observed seismic data. Having both Synthetic and observed seismic data displayed on the same software facilitated the synthetic-vs-observed seismic comparison process.

CHAPTER 7

SYNTHETIC VS. OBSERVED SEISMIC DATA COMPARISON

Synopsis

This chapter shows the synthetic vs. observed seismic data comparison results. Both observed and synthetic seismic data are displayed in a Shell Australian polarity convention where a downward increase in acoustic impedance results in a trough, negative amplitude.

7.1 Observed Seismic vs. Sparse 2D Synthetic Seismic

During initial runs, Sedsim was run for the study area from the Pre-Aptian Basement up to the Turonian Unconformity, not all way to seabed. In addition, it was run with sparse node spacing. One 2D line from Sedsim stratigraphic model was converted to a 2D synthetic seismic line and was displayed in MATLAB. The synthetic 2D seismic line was too sparse to be compared with its corresponding observed 2D line. Therefore, one trace from the synthetic 2D line was compared with its corresponding trace from the observed seismic data.

The comparison showed a degree of similarity between the two traces. However, there were some issues. There was a time mis-tie between the two traces, about 100 milliseconds. Moreover, some reflections were absent from the synthetic trace (Figure 7.1).

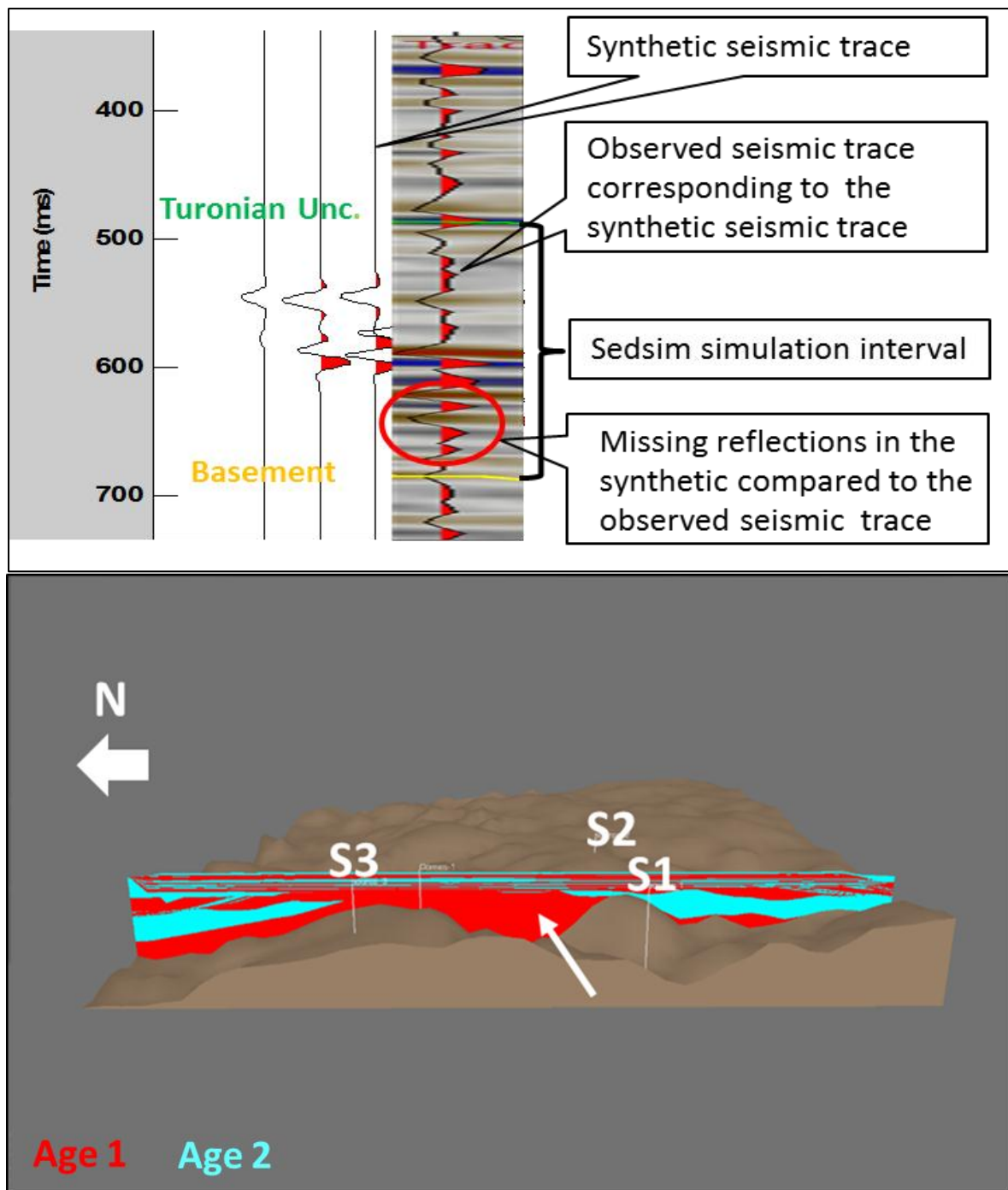


Figure 7.1: Top: an observed seismic trace compared to a synthetic seismic trace showing a degree of similarity but some missing reflections. Bottom: a Sedsim line from which the synthetic seismic trace was generated showing an interval where a thick layer was deposited in a short time (pointed by white arrow). Red and blue indicate different ages.

Based on the comparison above, Sedsim model was investigated. It was found that a thick layer was allowed to deposit within a very short time, which was geologically not plausible. This was thought of

as the probable cause of the absence of some reflections in the synthetic seismic trace. As a result, Sedsim was rerun after the adjustment of some parameters to allow for the deposition of more layers.

The rerun resulted in more layers within the Sedsim model. The model was then converted into synthetic seismic data and the missing reflections were successfully restored.

7.2 Observed Seismic vs. 3D Synthetic Seismic

At later stages of the study, Sedsim was run all the way from the Pre-Aptian Basement to seabed. It was run with 50-meter node spacing only for one square kilometre of the study area. For the rest of the study area, it was run with 100-meter node spacing. The model was then used to generate a 3D synthetic seismic volume (Figure 7.2).

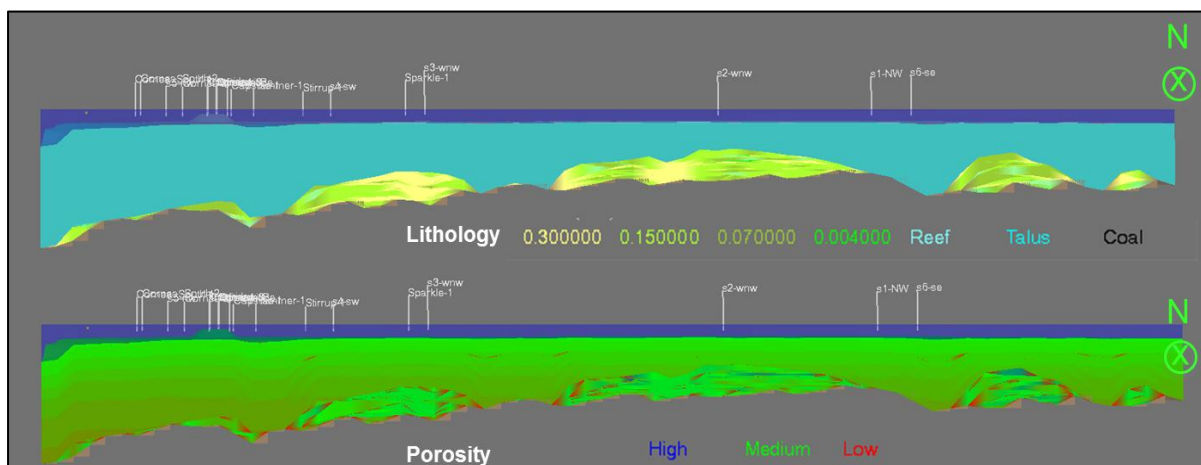


Figure 7.2: Side view of Sedsim model run from the Pre-Aptian Basement all the way to seabed. The colours in this display are indicative of lithology and grain size (top) and porosity (bottom) while dark blue indicates water.

Comparison between 3D observed and synthetic seismic data within the 50-meter-node-spacing area, showed a great degree of similarity between the two data sets especially within the target area, from the Pre-Aptian Basement to the Turonian Unconformity. The Pre-Aptian Basement resulted in a strong trough similar to that of the observed seismic while the Turonian Unconformity, between soft

shale and harder sand, respectively, resulted in a strong peak again similar to that of the observed seismic (Figure 7.3 & Appendix K).

The synthetic seismic data reflects the general stratigraphic pattern observed in the observed seismic data: a Pre-Aptian basement overlain by Albian sediments (Figure 7.3) (Moby Oil and Gas Ltd, 2009).

Synthetic seismic amplitudes within the target area are slightly stronger than those of the observed seismic. This could possibly be a result of a slight over estimation of velocities or densities. In addition, synthetic seismic data was generated using a 50-Hz Ricker wavelet. The choice of a 50-Hz Ricker wavelet was arbitrary. The comparison shows that a higher frequency wavelet should have been used for even better results. The use of the 50-Hz Ricker wavelet resulted in lower frequency content in synthetic seismic than in the observed one. Nevertheless, the observed-vs-synthetic seismic data comparison in this case shows an overall great degree of similarity (Figure 7.3).

However, there were some issues. There was a 200-millisecond time mis-tie between observed and synthetic data. In addition, amplitudes within the carbonate-dominant interval, above the Turonian Unconformity and below seabed, were very weak compared with those from the observed data (Figure 7.3).

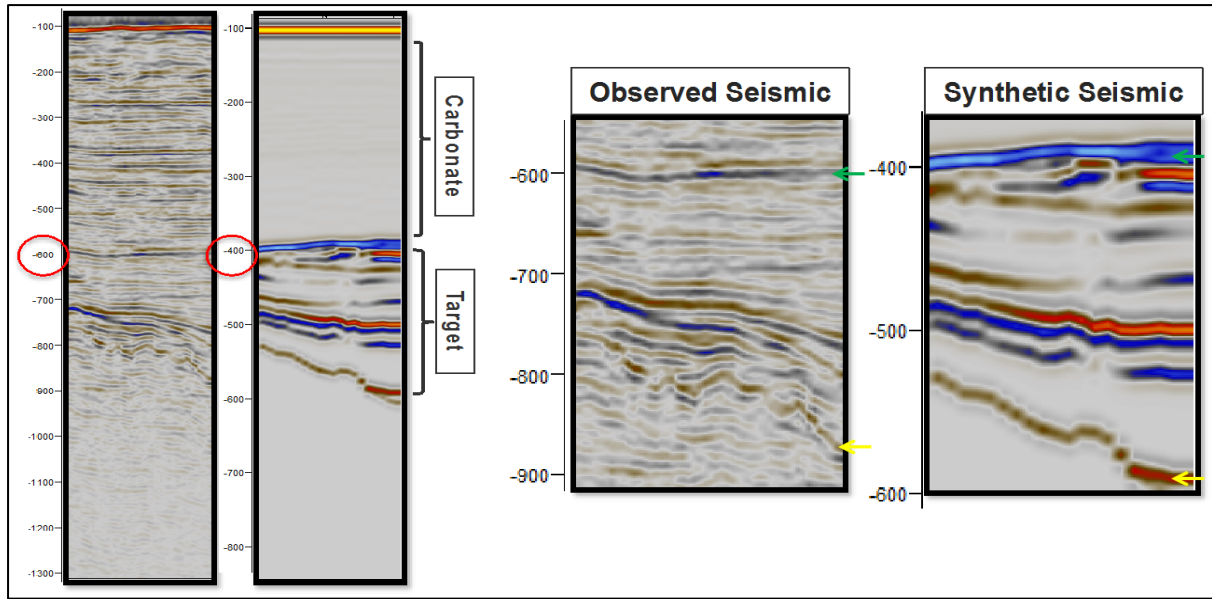


Figure 7.3: A comparison between synthetic and observed seismic data shows weak reflections within the carbonate-dominant interval. In addition, it shows an approximately 200 milliseconds time mis-tie between the two data sets (left). Nevertheless, the comparison shows a great degree of similarity within the target area. The green arrows point to the Turonian Unconformity seismic event while the yellow arrows point to the basement seismic event (right).

As mentioned before, the velocity-porosity-clay (VPC) rock physics model utilized in this study is designed for sandstones and not necessarily for carbonates. The problem of weak or almost lack of reflections within the carbonate-dominant interval in addition to the time mis-tie are possibly due to the incompatibility of the VPC within the carbonate-dominant interval from the Turonian Unconformity to seabed. Using an incompatible rock physics model can lead to calculating inaccurate velocities, which can, in turn, lead to problems such as weak amplitudes and time mis-ties as observed in this study. Other causes i.e. causes within the Sedsim model for such problems are possible but before such causes are explored, a compatible rock physics model must be used within the carbonate-dominant interval.

In this study, the target interval is between the Pre-Aptian Basement and the Turonian Unconformity, well below the carbonate-dominant interval. This interval is compatible with the VPC. In addition, synthetic seismic within this interval shows a great degree of similarity when compared with observed

seismic. Therefore, the results were not recalculated within the carbonate-dominant interval using a different rock physics model. Instead, this was left as a recommendation for future work.

7.3 Observed Seismic vs. Final 3D Synthetic Seismic

Since each Sedsim node corresponds to a seismic trace, the plan was, initially to generate a Sedsim model with node spacing equivalent to observed seismic trace spacing, 12.5 meters. However, based on the machine run time of the previous results (Section 7.2), it was concluded that such run would be time consuming. In addition, the previous comparison shows that a 50-meters Sedsim node spacing over an area of one square kilometre is sufficient for a qualitative observed versus synthetic seismic data comparison. Furthermore, the run from the previous section showed good results within the target interval (Figure 7.3).

Therefore, instead of creating a whole 3D synthetic volume, a number of one square kilometre synthetic seismic volumes with 50-meter node spacing similar to the one created in the previous section were generated over the study area (Figure 7.4).

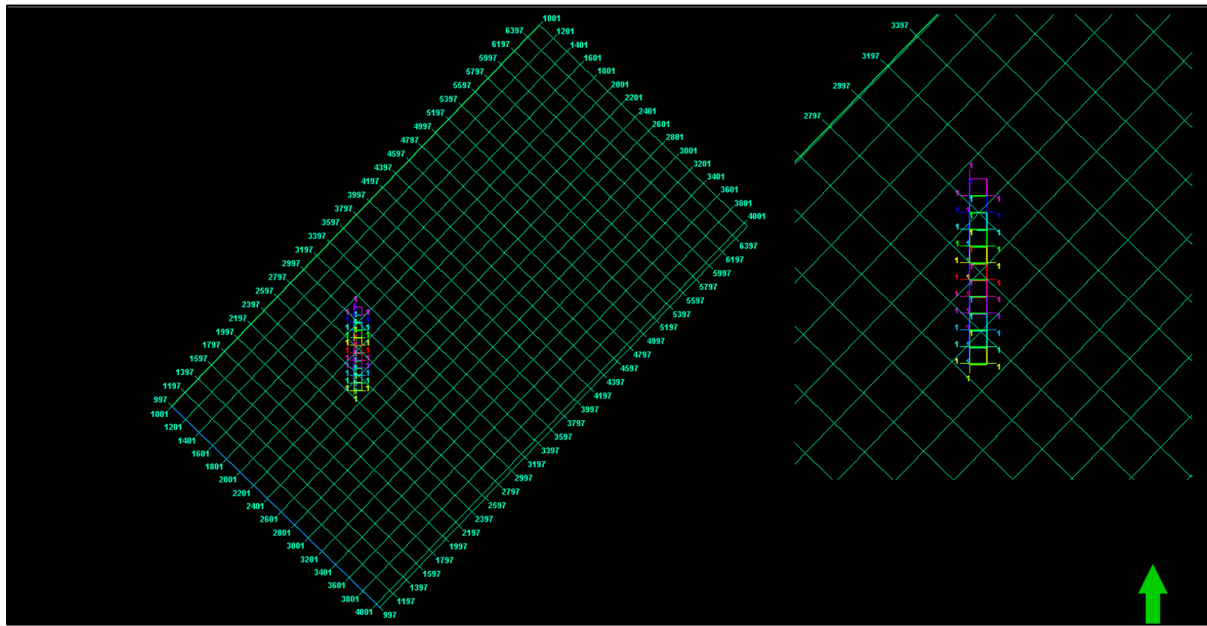


Figure 7.4: 3D observed seismic coverage (large green frame) (left). Eleven one-square-kilometre synthetic seismic volumes were generated within the observed seismic coverage area (colourful squares) (right).

Synthetic seismic data from these volumes were compared to their corresponding observed seismic data. The results generally showed a good degree of similarity within the target interval. Since these volumes were generated from the previous run (Section 7.2) i.e. no Sedsim parameters were modified, the one square kilometre volume in the previous section (Figure 7.3) can be taken as one example of these volumes. The rest of the data was run with 100-meter node spacing.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Synopsis

This chapter discusses whether the objective was met. It also sheds light on possible applications of the results. In addition, it states important conclusions, recommendations and possible future work.

8.1 The Main Objective

Closing The Loop: The main objective of this study was to assess and reduce the uncertainty in the stratigraphic model by closing the loop i.e. by comparing observed seismic with corresponding synthetic seismic generated from the stratigraphic model. Adjustments and modifications are then made to the stratigraphic model based on the results of the comparison. The process is repeated until a “good match” between the observed and synthetic seismic data is achieved.

The previous chapter (see chapter 7) shows two examples of how comparison between observed and its corresponding synthetic seismic data helped achieving the main objective. The first example is a comparison between an observed seismic trace and its corresponding synthetic trace. The example shows absence of reflections within the synthetic trace when compared with the observed trace. Consequently, adjustments were made to Sedsim parameters to allow for the deposition of more layers.

In the second example, comparison between observed and synthetic seismic data shows a time mis-tie between the two data sets. It also shows extremely weak reflections within the carbonate-dominant interval above the Turonian Unconformity. After analysing and testing possible sources of such mismatch between the two data sets, it was concluded that Sedsim parameters may need to be adjusted but before this is done, a carbonate-compatible rock physics model must be applied within the carbonate-dominant interval. Although this was not carried out in this study (due to time constraints), it was the process of closing the loop via which the weak reflections and the time mis-tie problems were pointed out.

The two examples above (detailed in chapter 6) show that based on this comparison, an area of uncertainty within the stratigraphic model is defined. The stratigraphic model can then be modified to reduce uncertainty i.e. the loop was closed. Therefore, the main objective of this study is met.

Nevertheless, the expectation in this study was to use the process of closing the loop iteratively until uncertainty in the stratigraphic model is greatly reduced. However, instead of iterative utilization, the process of closing the loop was used only twice to define and thus reduce uncertainty in the stratigraphic model. The main reason behind this non-iterative use was time. In order to clarify, I break the process of closing the loop into three parts. Assuming a of a reasonable Sedsim stratigraphic model, where errors are hard to spot by viewing the model, has already been generated, I classify each part in terms of time consumption (low, medium and high) as follows.:

Converting the stratigraphic model into seismic: The process of converting the stratigraphic model into seismic data i.e. seismic forward modelling was achieved by converting each Sedsim node into a seismic trace. The whole process was coded in MATLAB. In terms of time consumption, I classify this part as low.

Comparing the generated synthetic seismic with the observed one: The synthetic-vs-observed seismic data comparison was qualitative. Synthetic seismic data was displayed next to observed seismic data and conclusions were derived. I classify this part as low in terms of time consumption.

Modifying the stratigraphic model based on comparison results: Uncertainty in the stratigraphic model was relatively quickly identified based on the observed-vs-synthetic seismic data comparison results. However, minimizing the uncertainty involved many runs of trial and error until the uncertainty was reasonably minimized. In addition, the large area over which the model was created and the high resolution of the model in terms of grid size and number of nodes made the runs highly time consuming. Therefore, I classify this part as high in terms of time consumption. As an example, one of the 2D runs took 14 hours 12 minutes and 49 seconds for the simulation time interval 120 Ma

to 106.8 Ma at a temporal resolution of 200 ka. This coarse grid had a resolution of 500 m over a grid of 2500 cells, in which was embedded a 1600 cell fine grid at 50 m resolution around the Cornea wells. The machine used was a water-cooled HP Envy 810-110a Core i7 Tower with 8 physical cores, 16 GB memory, running Ubuntu 14.04 able to run 12 Sedsim simulations simultaneously.

Based on the above, I conclude that the process of closing the loop is practical in terms of identifying uncertainty. However, finding the correct Sedsim parameters to modify in order to reduce the identified uncertainty in addition to re-running the Sedsim model can be time consuming. The run time problem can be overcome by reducing some Sedsim parameters such as grid size or by breaking the modelled area into smaller parts.

8.2 Secondary Objectives

Stratigraphic Model: The generated stratigraphic model is an immediate result of this study. The Uncertainty of the model is evaluated and reduced as possible using the process of closing the loop. Once a good match between observed and synthetic seismic data is achieved, the stratigraphic model is ready for use for exploration and development purposes within the target interval.

Stochastic Inversion: In addition to achieving the main objective, closing the loop, the results may be applied in different areas such as stochastic inversion. In stochastic inversion, a number of realizations are generated. Each realization corresponds to a different geologic scenario. One realization is chosen as input into the inversion process. The results of this study can be used to constrain the number of realizations to select from.

Once a good match between observed and synthetic seismic is achieved, it is assumed that the stratigraphic model is reasonably accurate. This stratigraphic model is then compared with stochastic inversion realizations. Realizations that result in a good match when compared with the stratigraphic model are kept while those that don't are filtered out. In other words, the comparison between the

stratigraphic model and the realizations can serve as a criterion based on which stochastic inversion input is selected. In the case of this study, this is true at least within the target interval.

8.3 By-products

In the case of this study, it must be emphasized that some of these by-products may not be usable, at least not entirely, until the results are recalculated using a compatible rock physics model within the carbonate-dominant interval. The new results must then go through the process of closing the loop until a satisfactory outcome is achieved.

Velocity Cube: During this study some useful by-products were generated such as: velocity cube. In order to generate 3D synthetic seismic data, compressional and shear velocities were calculated for each depth interval at each Sedsim node resulting in the calculation of a velocity cube.

Every time the loop is closed i.e. the stratigraphic model is modified, the velocity cube is modified as well. Therefore, when a good match between observed and synthetic seismic data is finally achieved, the velocity cube is assumed to be of reasonable accuracy.

This velocity cube can be used for future processing of seismic data. In addition, it can be used to convert the seismic time volume to a depth volume.

Synthetic Seismic Data: During this study reasonably accurate synthetic seismic data was generated. The accuracy of the generated data is evaluated by comparison with the observed data. Generally, synthetic seismic data is “cleaner”, less noisy, compared to observed data. Therefore, synthetic data can be used instead of observed data wherever the latter is too noisy.

In addition, when observed seismic volumes contain areas of missing traces, which are not acquired due to obstacles within acquisition area. Since there are usually no missing traces in synthetic seismic data, it can be used to predict traces within areas of missing traces.

8.4 Assumptions

Water-Saturated Porosity: It was assumed in this study that all porosity is water-saturated. This assumption was made since Sedsim is unable to simulate hydrocarbon flow. Therefore, fluid saturation cannot be derived from Sedsim stratigraphic model.

Theoretically, this assumption can have its toll on the velocities and hence on the generated synthetic seismic data. However, in practice, tests need to be run in order to learn more about the effect of this assumption on the generated synthetic seismic. For example, synthetic seismic data could be generated assuming oil-saturated or gas-saturated porosity instead of water. The three different synthetic seismic data sets (water-, oil- and gas-saturated) could then be compared to get a sense of how different fluids can change final results.

VPC Rock Physics Model above Turonian Unconformity: The Velocity-Porosity-Clay rock physics model was designed to deal with clay-rich sandstones (Goldberg & Gurevich, 1998). It was, however, applied to whole geologic section including the carbonate-dominant interval above the Turonian Unconformity. Ideally, a different rock physics model should have been used, one that is designed for carbonate rocks. But since the main target reservoir in this study is below the Turonian Unconformity and since practical knowledge on the compatibility of VPC with carbonate rocks was limited, VPC was assumed to work for the whole geologic section.

Obviously, using the “wrong” rock physics model may result in the wrong velocities and hence affect the final synthetic seismic results. Therefore, a rock physics model suitable for the carbonate rock should be applied within the carbonate-dominant interval.

Seabed Depth: Water is not deposited as a layer within Sedsim. Therefore, seabed reflection, the reflection corresponding to the boundary between water and seafloor, is not generated directly. Instead, water is added after Sedsim model is generated. In order to add water layer, depth from sea level to seabed must be known. Seabed depth was assumed to be constant all over the study area. In

particular, it was set to be 83 meters TVDSS based on well Cornea-1. This assumption resulted in a straight-line looking seabed reflection in the generated synthetic seismic data. Fortunately, the observed seismic data shows an almost flat reflection with only slight dipping (Figure 8.1). Therefore, this assumption did not result in any significant impact on the data. However, ideally water-to-seabed depth should have been predicted more accurately. Perhaps one way of doing this in the future would be by depositing water as an initial layer within Sedsim.

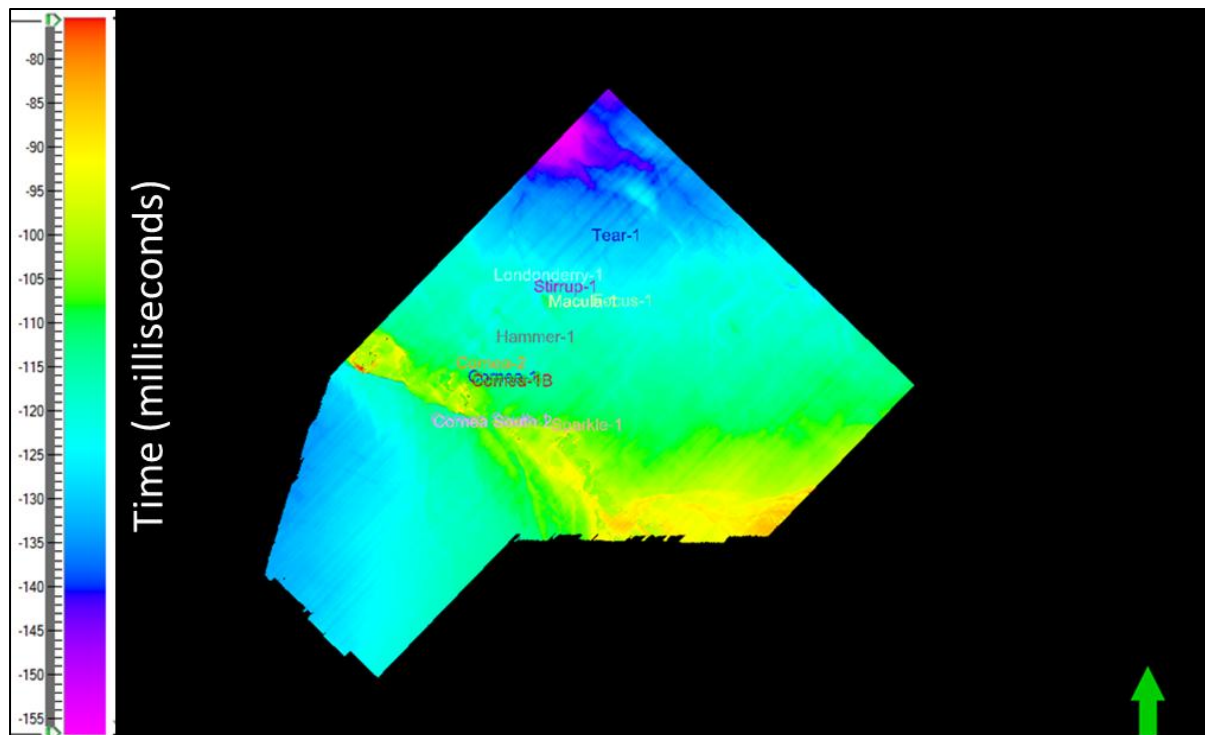


Figure 8.1: Seabed time horizon over the Cornea field showing no significant variation.

8.5 Conclusions

Numerical stratigraphic forward modelling is a powerful and quantitative technique for modelling the subsurface. Unlike traditional geologic modelling, it is deterministic; it attempts to model sediments by simulating geological processes that lead to their deposition. Many iterations or runs are needed before initial satisfactory results are achieved.

Despite powerful, numerical stratigraphic modelling comes with uncertainty. This study showed that the uncertainty within the generated stratigraphic model can indeed be evaluated and reduced by “closing the loop”: modifying the stratigraphic model parameters based on the comparison of observed seismic data and synthetic seismic data generated from the stratigraphic model using a suitable rock physics model. The process of closing the loop was repeated until a reasonable match between observed and synthetic seismic data was achieved within the target interval. Once such match was achieved, the stratigraphic model was assumed ready for use.

In order to make sure that a reasonable observed-synthetic seismic match is solely a result of a reasonable stratigraphic model, input from observed seismic data was limited to one horizon only, the Pre-Aptian Basement. In addition, log data was not used as direct input into Sedsim model.

The Process of closing the loop has applications in different areas such as in stochastic inversion. In addition, useful by-products such as velocity cube are generated during this process.

Qualitative comparison between observed and synthetic seismic data within the target interval where the VPC rock physics model was suitable showed a great deal of similarity. Within the carbonate-dominant interval, with which, the VPC was not compatible, observed and synthetic seismic data differed. In addition, there was a time mis-tie between the two data sets.

In conclusion, good results were achieved within the target area, from Pre-Aptian Basement to Turonian Unconformity. In order to better these results for the carbonate-dominant interval and resolve the time mis-tie, a rock physics model compatible with the carbonate-dominant interval must be utilized. The resultant synthetic seismic must then go through the process of closing the loop until satisfactory results are achieved.

8.6 Recommendations

This study assumed that the Velocity-Porosity-Clay (VPC) rock physics model works for carbonate-dominant interval above the Turonian Unconformity. It also assumed that all porosity is water-saturated. I recommend a different rock physics model, one that is designed for carbonate rocks in order to generate more accurate velocities and synthetic seismic. As for the saturation, SedSim Software is currently being modified to model hydrocarbon migration. Once SedSim is able to model hydrocarbon migration, I recommend rerunning the stratigraphic model and going through the process of closing the loop again.

Qualitative comparison between observed and synthetic seismic data is a good comparison technique. However, I recommend inverting the observed seismic data into acoustic impedance. Acoustic impedance from observed seismic can then quantitatively compared with its corresponding acoustic impedance from the synthetic seismic. Unfortunately, due to time limitations, I could not invert the observed seismic data.

I also recommend using more powerful machines in order to be able to run larger high resolution volumes.

8.7 Possible Future Work

The process of closing the loop can generate reasonably accurate synthetic seismic data, comparable to the observed seismic data. Synthetic seismic data, however, is usually “cleaner”, less noisy, than observed seismic data. Based on that, in the future, should we routinely use the process of closing the loop, generate synthetic seismic data and rely more on synthetic seismic data for exploration and development purposes? Should we generate reasonably accurate synthetic seismic data using the process of closing the loop instead of re-acquiring observed seismic data?

REFERENCES

- Al-Siyabi, Q., Gurevich, B. & Madadi, M., 2012, Rock physics approach to synthetic seismic generation from sedimentary process modelling, private communication.
- Anderson, N. & Cardimona, S., Forward Seismic Modelling: The Key to Understanding Reflection Seismic and Ground Penetrating Radar (GPR) Techniques, p. 20.
<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.133.2457&rep=rep1&type=pdf>
- Avseth, P., Mekurji, T. & Mavko, G., 2005, Quantitative Seismic Interpretation: Applying Rock Physics Tools to Reduce Interpretation Risk, p. 15-23, p. 42-47.
- Bohling, G., 2005, Introduction to Geostatistics and Variogram Analysis,
<http://people.ku.edu/~gbohling/cpe940/Variograms.pdf>
- Cantrell, D., Griffiths, C. M., , Hughes, G. W., 2015. New Tools and Approaches in Carbonate Reservoir Quality Prediction. In (eds) Agar, S. M. and Geiger S., Fundamental Controls on Fluid Flow in Carbonates: Current Workflows to Emerging Technologies, Geol Soc London and AAPG Special Publication 406, 401-426, First published online August 13, 2014
<http://dx.doi.org/10.1144/SP406.15>
- CSIRO Petroleum., 2003, Sedsim Stratigraphic Forward Modelling,
https://wiki.csiro.au/confluence/download/attachments/160891382/Sedsim_background.pdf
- Fallara, F., Legault, M. & Rabeau, O., 2006, 3-D Integrated Geological Modeling in the Abitibi Subprovince (Québec, Canada): Techniques and Applications, Exploration and Mining Geology, Vol. 15, Nos. 1-2, p. 27-41.
- Geoscience Australia, 1997, Well Completion Report, Well Name: Cornea 1, 1B, 2.

Goldberg & Gurevich, 1998, A semi-empirical velocity-porosity-clay model for petrophysical interpretation of P- and S-velocities, *Geophysical Prospecting*, 46, 271-285.

Griffiths, C. M., Dyt, C., Paraschivoiu, E. & Liu, K., 2001, Sedsim in hydrocarbon exploration in Merriam, D., Davis, J. C. (eds) *Geologic Modelling and Simulation*. Kluwer Academic, New York, p.71-97.

Griffiths, C. M. & Paraschivoiu, E., 1998. Inner Browse Basin Depositional Modelling, National Centre for Geology and Geophysics, p.10-25.

Griffiths, C. M. & Hadler-Jacobsen, F., 1993, Practical Dynamic Modelling of Sequence Stratigraphy. In: Steel, R. et al. (eds) *Sequence Stratigraphy: Advances and Applications for Exploration and Production in North West Europe*, Norwegian Petroleum Society.

Griffiths, C.M. & Dyt, C., 2001, Six Years of Sedsim Exploration Application (Abstract Only), *AAPG Bulletin*, 85(001), p. 13.

Griffiths, C. M., and Paraschivoiu, E., 1998, Three-dimensional forward stratigraphic modelling of Early Cretaceous sedimentation on the Leveque and Yampi Shelves, Browse Basin. *The APPEA Journal*, 38, 1, p.147-158.

Griffiths, C.M. and Smith, D.G., 1993, Nonlinear dynamics in stratigraphic modeling - order from Chaos. *AAPG Bulletin* (American Association of Petroleum Geologists), Volume: 77:9, ISSN 0149-1423; CODEN: AABUD2

Gurevich, B., 2015, private communication.

Gurevich, B., Gerhardt, A., Lambert G., Griffiths, D.M. & Dyt, C. 2006, Numerical modelling of seismic character of depositional sequences, EAGE Internat. Geophys. Conf. Exhib., Saint-Petersburg, Russia, 16-19 October 2006, Expanded Abstracts, paper 1092.

Huang, X., Griffiths, C. M., Liu, K., 2014 (in review). Recent advances in stratigraphic forward modelling and its application to modern petroleum exploration. *Petroleum Science*, 11,

Kearey P., Brooks M. & Hill I., 2002, *An Introduction to Geophysical Exploration*, p. 48-49.

Lambert, G., Gurevich, B. & Brajanovski, M., 2006, Attenuation and dispersion of P-waves in porous rocks with planar fractures: Comparison of theory and numerical simulations, 71(3), N41-N45.

Marita Bradshaw, 2008, New opportunities for offshore petroleum exploration, *AusGeo News*, Issue No. 90.

<http://www.ga.gov.au/ausgeonews/ausgeonews200806/acreage.jsp>

Mavko, G., Mukerji, T. & Dvorkin J., 2009, *The Rock Physics Handbook: Tools for Seismic Analysis of Porous Media*, p. 169-174, p. 243, Table A.4.1.

Moby Oil and Gas Ltd, 2009, Independent Geologist's Report of WA-342-P (Cornea Field), WA-332-P/WA-333-P (Braveheart Prospect), WA-360-P (Artemis Prospect) And WA-409-P, Australia, 24-3.

Ravesteyn, J. J., Griffiths, C. M., Dyt, C. P., Michael, K., 2014 (in review) Multiscale Stratigraphic Forward Modelling in the Surat Basin for Geological Storage of CO₂. *Terra Nova*

Yarus, J. M., 2009, Geocellular Modeling, *Search and Discovery Article #120015*, abstract
http://www.searchanddiscovery.com/pdfz/documents/2009/120015yarus/ndx_yarus.pdf.html

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APPENDICES

Appendix A: Main Code

```
clear all ;
% Mohammed Alkaff, Roman Pevzner, Mahyar Madadi & Andrej Bona
% Note: This code is used to generate acoustic properties using this
% Sedsim output and the proposed VPC model. This Sedsim output is
% from
% Cornea Field NW of Australia and it is provided by CSIRO.
% It consists from eight different grain sizes (e.g.
% gr1(m),gr2(m),gr3(m),...gr8(m)).

% gr1(m) - - - - gr4(m) are the thicknesses in metres of each of
% the four
% siliciclastic grains deposited in that time interval.

% gr5(m), gr6(m) are the thicknesses in metres of each of the two
% carbonate grains deposited in that time interval. These are Zero.

% gr7(m), gr8(m) are the thicknesses in metres of each of the two
% organic
% grains deposited in that time interval. These are also zero.

% Note: gr1(m) - - - - gr4(m) have different grain diameter.

% gr1(m) = 0.3 mm --> Coarse sand, using Udden-Wentworth scale
% gr2(m) = 0.15 mm --> medium sand, using Udden-Wentworth scale
% gr3(m) = 0.07 mm --> fine to very fine sand, using Udden-
% Wentworth scale
% gr4(m) = 0.004 mm --> very fine Clay, using Udden-Wentworth scale
% --> (Mavko et al., 2009).

% First, we set the elastic parameters from VPC model.

rho_sand = 2650.00 ; % Kg/m^3
rho_clay = 2050.00; % Kg/m^3
rho_water = 1200; % Kg/m^3
rho_carb = 2700; % Kg/m^3
rho_org = 2700; % Kg/m^3
% rho_org = 2450; % Kg/m^3

K_quartz = 39.0281; % GPa
K_clay = 24.6454; % GPa
K_calcite = 71; % GPa

% finding minimum bulk modulus for H-S lower bound
K_min = min([K_quartz, K_clay, K_calcite]);

mu_quartz = 32.8346; % GPa
mu_clay = 14.1285; % GPa
mu_calcite = 30; % GPa
```

```

%finding minimum shear modulus for H-S lower bound
mu_min=min([mu_quartz,mu_clay,mu_calcite]);

%setting VPC rock physics model constants Ao and A1
Ao=4;
A1=0;

dt = 0.001; %sampling interval
T_max = 1; %trace length in s
np=ceil(T_max/dt); % Number of samples is the maximum twtc divided
by sampling interval

df=1/(dt * np); % Calculate frequency interval
F=0:df:(np-1)*df; % Calculate frequency array
w=2*pi*F; % Calculate angular frequency array

Rfft = zeros(size(w)); % Create a matrix Rfft or FFT of R with same
size of previous arrays and fill it with zeroes

%Reading input data from Sedsim using MATLAB function fReadSedSim
[ind_un,col,
row,xcoord,ycoord,gf_flipped>Total_Porosity_flipped,dz,ltop,lbottom]
= fReadSedSim('cornea_100m_6x81.csv');
ncells = max(ind_un);
ncols = max(col);
nrows = max(row);

if (ncells ~= ncols*nrows)
    disp('Something went wrong');
    return;
end;

%Create an array to store traces later
output=zeros(np,ncells);

%define Ricker (or other) wavelet (and its spectra)
f_0 = 80; % central frequency of Ricker wavelet
[rw,t] = ricker(f_0,np,dt,T_max/2); % create a ricker wavelet with
f_0 Hz, np points, and dt s between samples
rwwfft=fft(rw); % FFT of Ricker wavelet

%set water depth, velocity and density
dz_w=83;
Vp_w=1500;
rho_w=1027;

%set basement velocity and density
v_b=3200;
rho_b=2450;

%converting each Sedsim node to seismic trace
for n = 1:ncells
    ccell = ind_un == n;

    if n == 27
        disp('yada');
    end
end

```

```

end;

ccol = col(ccell);
crow = row(ccell);
cx = xcoord(ccell);
cy = ycoord(ccell);
cgf = gf_flipped(ccell,:);
cTotal_Porosity = Total_Porosity_flipped(ccell);
cdz = dz(ccell);
cltop = ltop(ccell);
clbottom = lbottom(ccell);

%removing NaN data
for m = 2:length(cdz)
    if isnan(cgf(m,1))
        cgf(m,:) = cgf(m-1,:);
        cTotal_Porosity(m) = cTotal_Porosity(m-1);
    end
end;

% The solid fraction of the sand, carbonate, organic matter and
clay content within a volume can be
% computed as:
sf=(cgf(:,1)+cgf(:,2)+cgf(:,3)); %sand fraction
cf=(cgf(:,5)+cgf(:,6)); %carbonate fraction
orgf=(cgf(:,7)+cgf(:,8)); %organic matter fraction
C = cgf(:,4); %clay content

% Calculate Elastic Properties using VPC rock physics model
(MATLAB
% function: VPCFunc

[K_sat,Mu_sat,rho_sat]=VPCFunc(sf,C,cf,orgf,mu_min,K_min,K_quartz,
K_clay,
K_calcite,mu_quartz,mu_clay,mu_calcite,Ao,A1,cTotal_Porosity,rho_san
d,rho_carb,rho_clay,rho_org,rho_water);

% Calculate velocities
Vp = sqrt(10^9*(K_sat+4/3*Mu_sat)./rho_sat);
Vs= sqrt(10^9*(Mu_sat)./rho_sat);

% Add water depth, velocity and density at the start of each
vector
cdz=[dz_w;cdz];
Vp=[Vp_w;Vp];
rho_sat=[rho_water;rho_sat];

%compute AI
AI = Vp.*rho_sat;

twti=(cdz./Vp).*2; % Calculate interval twt for each Sedsim
interval

%calculate reflection coefficients
R=zeros(size(twti)); %creating a reflection coefficient vector

```

```

    for i=2:(length(twti)) % Calculate reflection coefficient at
each boundary
        R(i-1)=(((AI(i)-AI(i-1))/(AI(i)+AI(i-1)))).*-1;
    end

    %add basement
    AI_b=v_b*rho_b;
    R_base=(AI_b-AI(length(AI)-1))/(AI_b+AI(length(AI)-1));
    R(length(twti))=R_base*-1;

    %compute spectra of the trace
    twtc=cumsum(twti);
    for k=1:(length(twtc))
        Rfft=Rfft + R(k)*exp(-1i*w*(twtc(k))); % Calculate FFT of R
by multiplying each R by the imaginary component and summing
    end

    %convolve with Ricker
    Sfreq=Rfft.*rwfft.*exp(-1i*w*T_max/2); % Element multiplication
of each FFT reflection with corresponding FFT Ricker wavelet to
give seismic in frequency domain

    %back to time domain
    Stime=ifft(Sfreq,'Symmetric'); % Converting seismic from
frequency domain to time domain

    %storing trace in "output"
    output(:,n)=Stime;

    %setting Rfft and twtc to zero to prepare for the next trace
    Rfft = zeros(size(w));
    twtc=0;
end;

% plotting seismic data
figure(1);
imagesc(fliplr(output));

% preparing input to write "output" as segy
[Xc,ia,ic] = unique(xcoord);
[Yc,ib,id] = unique(ycoord);

tmp = repmat(Xc,1,length(Yc));
cdpX = tmp(:);
tmp = repmat(Yc',length(Xc),1);
cdpY = tmp(:);

[Inline,Crossline] = meshgrid(1:size(tmp,1),1:size(tmp,2));

%writing file as segy using SegyMAT (CREWES)
WriteSegy('cornea_clrawa3.segy',fliplr(output),'dt',dt,'Inline3D',In
line(:),'Crossline3D',Crossline(:),'cdpX',cdpX,'cdpY',cdpY);

```

Appendix B: VPC Rock Physics Model Code

```

function
[K_sat,Mu_sat,rho_sat]=VPCFunc(sf,C,cf,orgf,mu_min,K_min,K_quartz,
K_clay,
K_calcite,mu_quartz,mu_clay,mu_calcite,Ao,A1,cTotal_Porosity,rho_sand,
rho_carb,rho_clay,rho_org,rho_water)

%Calculating effective bulk and shear moduli using H-S lower bound
for the
%mixture (part 1)
sandpart1=sf./(K_quartz+4/3*mu_min);
claypart1=C./(K_clay+4/3*mu_min);
carbpart1=cf./(K_calcite+4/3*mu_min);
orgpart1=orgf./(K_calcite+4/3*mu_min);
thirdpart1=4/3*mu_min;
sumpart1=(sandpart1+claypart1+carbpart1+orgpart1);
sumpartinv1=(sumpart1).^(-1);

ksi=(mu_min/6)*((9*K_min+8*mu_min)/(K_min+2*mu_min));
sandpart2=sf./(mu_quartz+ksi);
claypart2=C./(mu_clay+ksi);
carbpart2=cf./(mu_calcite+ksi);
orgpart2=orgf./(mu_calcite+ksi);
sumpart2=(sandpart2+claypart2+carbpart2+orgpart2);
sumpartinv2=(sumpart2).^(-1);

%calculating VPC constants Ao and A1
A=Ao + A1.* C.^2;

%Calculating effective bulk and shear moduli using H-S lower bound
for the
%mixture (part 2)
mu_eff = sumpartinv2-ksi;
K_eff = sumpartinv1-thirdpart1;

% Calculating K_dry using Krief's relations
K_dry = K_eff.*((1.-cTotal_Porosity).^(A./(1.-cTotal_Porosity))); %
Bulk Modulus of sand (GPa)
Mu_dry = mu_eff.*((1.-cTotal_Porosity).^(A./(1.-cTotal_Porosity)));
% Shear Modulus of sand (GPa)

% Calculate Bulk Density
rho_eff = sf.*rho_sand + C.*rho_clay + cf.*rho_carb +
orgf.*rho_org; % Kg/m^3

% Calculate K_sat and Mu_sat:
% First, we need to caculate Boit-coefficient
B = (1-(K_dry./K_eff));

% Calculate M
%fluid substitution
M = ((B-cTotal_Porosity)./K_eff + (cTotal_Porosity/2.57)).^(-1); %
K_water = 2.57 Gpa

```

```
K_sat = K_dry + B.^2.*M;  
Mu_sat = Mu_dry;  
  
%Calculate saturated density  
rho_sat = rho_eff.*(1-cTotal_Porosity)+rho_water*cTotal_Porosity;
```

Appendix C: Sedsim File Reading Code

```
function [ind_un,col, row,  
xcoord,ycoord,gf,Total_Porosity,dz,ltop,lbottom] =  
fReadSedsim(fname)  
  
D = dlmread(fname, ', ', 2, 0)';  
  
un = D(1,:) * 1e6 + D(2,:);  
  
ind_un = index(un);  
ncells = max(ind_un);  
  
for n = 1:ncells  
    ccell = ind_un == n;  
    D(:,ccell) = fliplr(D(:,ccell));  
end;  
  
data = D';  
clear D;  
  
xcoord = data(:,3);  
ycoord = data(:,4);  
  
col = data(:,1);  
row = data(:,2);  
  
gf(:,1) = abs(data(:,7)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,2) = abs(data(:,8)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,3) = abs(data(:,9)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,4) = abs(data(:,10)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,5) = abs(data(:,11)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,6) = abs(data(:,12)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,7) = abs(data(:,13)) ./ sum(abs(data(:,7:14)), 2) ;  
gf(:,8) = abs(data(:,14)) ./ sum(abs(data(:,7:14)), 2) ;  
Total_Porosity = data(:,15);  
dz = data(:,19) - data(:,18);  
lbottom = data(:,18);  
ltop = data(:,19);
```

Appendix D: Index Code

```
function [ind] = index(vec)

size_vec = size(vec);
n_entries = max(size_vec);

if (min(size_vec) > 1)
    ind = NaN;
    disp('should be a vector');
    return;
end;
[s_vec,s_ind] = sort(vec);

ind = zeros(size_vec);
count = 1;
ind(s_ind(1)) = 1;
p_val = s_vec(1);

for n=2:n_entries
    if abs(p_val - s_vec(n))>1e-3
        count = count + 1;
        p_val = s_vec(n);
    end;
    ind(s_ind(n)) = count;
end;
```


Appendix E: Sedsim Final Input Text File

```
#####
#                               Required parameters section                               #
#####
# Cornea
TITLE
# One-line title / comment on experiment                                     (required)
#
#       cornea_oxfordian2now_cm31f      from cornea_oxfordian2now_cm31
#
#       cm31f      larger 50m grid across the channel 41x41 and more time
steps
#       cm31       fine grid at 50 m using interpolation only
#       cm30       back to 0.004 for G4
#       cm29       move source5 to slope NW of cornea-1 flowing to NW
instead of SW to fill thge depression
#               likewise move s6 to close to s1 but flowing se to fill
that depression
#               change to linear subsidence - not bathymetry-based -
for interval 112-53 Ma to reduce mounding
#       cm27       increase base level by 10m to +35 - change compaction
to 100 m burial
#       cm26       not good result - too little sediment in valley
#       cm25       tectonic file from -120 to present
#               change base level to +25 to bring more water cover to
the valley
#               results- broad pattern OK but need more clastics
before carbonate onset
#       cm24       corrected clay grain size to 0.0004 from incorrect
0.004
#       cm23       new Aptian islands on new bathymetry
#       cm22       moved s1 3000 m west
#       cm21 - with carbonates above 56 Ma (Base Eocene) and turn off
clastics and waves
#
#       cornea_oxfordian2now_cm20      from      cornea_oxfordian_16fg
#
#       cornea_oxfordian2now_cm20      -112 Ma to surface at 1 Ma interval
and
#       100000 flow sampling
#       cornea_oxfordian_16fg -112Ma to 98Ma revised bathymetry
#
#       16fg - same as 16 with internal 21x21 grid of 50m spacing
#       16 - same as 15 with display interval of 100,000 and a flow
sampling interval of 5000
#       15 - same as 14 but with compaction on
#       14 - same as 13 but with waves on
#       13 - reduce flow rates and velocity /direction to more eastwards
from source 3
#       12      after 10 with source 1 flow parameters changed to reduce
erosion and source 3 location
#               and source 2 flowing due N
#       10      after 09 with wave turned off
#       09      after adding two more sources: Center and NW
#       08      with different source interval: 112 Ma to 98 Ma
```

```

# 07 with higher flow depth, and lower wave transport rates
# 06 with waves from WSW (220deg)
# 05 start from M Tetracantha at 112 Ma and run to 98 Ma
# 04 after 03 but source further N and 500 ka intervals and 50000
year fluid interval
# 03 after 02 but with Haq curve for sea level and vY to 0.20
# 02 - after 01 but with 44x44 grid including Cornea-1
#
#
#
# Include general comments about what modules are turned on and
# what is different in this simulation than previous iterations here
#
#-----
TIME
# Time parameters (required)
#
# Simulation start time [years] End time [years]
# -120000000 0
# -112000000 -98000000
#
# Display interval [years] Flow sampling interval [years]
# 200000 100000
# Display interval decides how often the results files are updated
# Flow sampling interval decides how often fluid elements are released
from the source
#-----
GRID
# Grid size definitions and geometry
#
# Grid spacing [m] Number of rows Number of columns
# 500.0 36 68
# Lower left (SW) corner coordinates Base level elevation
# 654850.0 8472850.0 35
# Topography grid file name
#
Cornea_Aptian_bathymetry_120Ma_36x68_rescaledto500m.top
#
#-----
--
TECTONICS
# Define tectonic movement (optional)
#
# Tectonic movement file name
# cornea_112-0Ma_linear_subsidence_36x68.tec
#
#-----
INTERNAL GRID
# experiment name for the internal grid.
cornea_oxfordian2now_cm31_fine_grid_50m
# x,y location of the grid (SW corner)
# 661217 8485273 Cornea-1
# 660850 8484350 finegridsw
# 661850 8485350 finegridne
#
# cmg31 fine grid
#660850 8484350

```

```

# grid spacing(m), number of fine row, number of columns
#50          21          21
# cmg31f    fine grid
661350      8484350
# grid spacing(m), number of fine row, number of columns
50          41          41
#-----
#INTERNAL TOPOGRAPHY GRID
# topography grid file name.
# If you have the internal grid turned on, you can specify the initial
surface
# if you don't do this, one will be generated from the coarse grid
cornea_50m_grid_surface.top
#-----
#INTERNAL GRID TECTONICS
# Define tectonic movement of the internal          (optional)
#
# Tectonic movement file name
<tectonic_movement_file>.tec
#
#-----
SEDIMENTS
# Sediment Parameters          (required)
#
# Line 1: Diameter of each grain size    [mm]
# Line 2: Density of each grain size    [kg/m3]
# Line 3: 1 - suspension (normal type), 0 - bed load
#
# pebble 4-64 mm, granule 2-4 mm, vcse 1-2 mm, cse 0.5-1 mm, med 0.25-
0.5 mm,
# fn 0.125-0.25, vfn 0.062-0.125 mm, slt 0.0039-0.062 mm, clay <
0.0039 mm
# MATLAB calculations
# gr2(m) = 0.3 mm --> Coarse sand, using Udden-Wentworth scale
# gr2(m) = 0.15 mm --> medium sand, using Udden-Wentworth scale
# gr3(m) = 0.07 mm -->fine to very fine sand, using Udden-Wentworth
scale
# gr4(m) = 0.0004 mm --> very fine Clay, using Udden-Wentworth scale
#      Coarse      Medium      Fine      Finest
#      0.3        0.15        0.07        0.004
#      2650.00    2650.00    2650.00    2650.00
#      1          1          1          1
#-----
POROSITY TABLE
# Porosity function          (optional)
#
# Number of entries in effective pressure look-up table
6
# Effective pressure look-up table [MPa]
0.0  10.0  20.0  30.0  40.0  50.0
# Number of entries in fine-to-coarse-ratio look-up table
12
# Fine-to-coarse-ratio look-up table
0.0  0.05  0.10  0.15  0.20  0.25  0.30  0.40  0.50  0.65  0.85  1.0
# Porosity look-up table
# must have the size of (pressures*ratios)
# rows: constant fine-to-coarse ratio
# columns: constant effective pressure

```

```

0.39 0.36 0.35 0.34 0.33 0.32
0.36 0.33 0.31 0.30 0.295 0.29
0.34 0.31 0.28 0.27 0.26 0.25
0.335 0.28 0.23 0.22 0.21 0.20
0.35 0.25 0.21 0.19 0.18 0.17
0.36 0.26 0.20 0.18 0.16 0.14
0.39 0.27 0.21 0.17 0.15 0.13
0.43 0.31 0.24 0.18 0.16 0.12
0.48 0.34 0.27 0.22 0.18 0.14
0.53 0.39 0.31 0.24 0.21 0.17
0.58 0.44 0.35 0.27 0.22 0.19
0.61 0.27 0.17 0.12 0.10 0.09
*
# Porosity table one row for each carbonate and organic
.50 .30 .20 .19 .18 .17
.35 .25 .21 .19 .18 .17
.60 .50 .40 .30 .20 .20
.20 .16 .13 .10 .05 .05
#
#
# Linear weighting coefficients for 4 grain sizes:
# r=Sum(h*w)/Sum(h)
# r fine-to-coarse ratio
# h thickness of individual grain size
# w linear weighting coefficient of individual grain size
# 4 coefficients(one for each siliciclastic grain):
0.0 0.0 1.0 1.0
#-----
-----
SOURCES
#
# Definition of sources that are constant throughout the experiment
(required)
# One line per source, entries are:
# Source location (x,y) [m]
# Velocity at source (vx,vy) [m/sec]
# Discharge rate (Q) [m3/sec]
# Sediment concentration (c) [kg/m3]
# Sediment composition (C coarse, [%]
# M medium,
# F fine,
# FF finest)
#
#ID# t1 t2 x y vx vy Q c
%C %M %F %FF
1 -112000000 -56000000 684350 8478250 -0.20 -0.20 5.0
0.2 5 25 35 35
2 -112000000 -56000000 678350 8477250 -0.24 -0.20 5.0
0.2 5 25 35 35
3 -112000000 -56000000 666850 8473250 -0.24 -0.20 5.0
0.2 5 25 35 35
#
4 -120000000 -112000000 667850 8490250 -0.14 -0.14 2.0
0.1 10 25 30 35
5 -120000000 -112000000 659350 8485850 -0.14 0.14 2.0
0.1 5 25 35 35
6 -120000000 -112000000 684850 8477350 0.24 -0.24 2.0
0.1 5 25 35 35

```

```

*
#####
# Additional module parameters (modules will not run if not included)
#####
#-----
SOURCE HEIGHTS
# list ends in '*'
# flow types 0=normal 1=turbidite 2=debris flow
# for debris flows the concentration must be high enough, otherwise
will
# transition to a turbidite (default transition at 60 kg/m3)
#
# source ID#   flow height(m)   flow type
#   1           5.0             0
#   2          10.0             0
#   3          10.0             0
#
#   4           5.0             0
#   5           5.0             0
#   6           5.0             0
*
#-----
WELL LOCATIONS
# locations in meters from Sedsim-grid origin (draws them in sedview)
# X Y
# well name
#
684350  8478350   s1-NW
678350  8477350   s2-wnw
666850  8473350   s3-wnw
667850  8490250   s4-sw
659350  8485850   s5-nw
684850  8477350   s6-se
#
# 659074  8479373 source_1
# 666009  8479868 source_2
# 659569  8486791 source_3
#
662779  8489711 Capsule-1
661217  8485273 Cornea-1
661537  8484924 Cornea-1B
660149  8486497 Cornea-2 checked on WCR
661603  8485159 Cornea-3
657885  8481473 Cornea_South-1
658105  8481252 Cornea_South-2
# 672382  8492083 Focus-1
663768  8488852 Hammer-1
# 663550  8494385 Londonderry-1
# 668441  8492028 Macula-1
668665  8480984 Sparkle-1
667099  8493358 Stirrup-1
# 672298  8497941 Tear-1
#
# 654850  8472850   SW_Corner   main 500 m grid
660850  8484350 finegridsw
661850  8485350 finegridne
#
* end of well data

```

```

#-----
PARAMETRIC SAMPLING INTERVAL
#         (optional)
#
# This should be seen in relation to temporal resolution - ie. think
aliasing
# Sampling interval for sea-level, rainfall and tectonics [y]
100000
#-----
CARBONATES AND ORGANICS
# Parameters for calculating carbonate development          (optional)
# (It is strongly recommended that waves are turned on with this module)
# calling interval (years)
100
# carb/org grain size diameter (one for each grain) after comminution
0.3 0.3 0.1 0.1
# carb grain density (one for each grain)
2760.00 2250.00 1800.0 1800.0
# temperature and salinity file (this is a list of year, sea surface
temperature[degrees C] and salinity [ppm])
# to let Sedsim interpolate between unknown values set them to -99
(warning: first value must always be defined)
# eg 2005 27.0 30000
# 2005.2 27.2 -99
# 2005.7 30.0 30250 etc.
# This line is ignored if TEMPERATURE GRID is used
#
Browse_SST_85Ma-0Ma.tmp
#
#-----
SEDIMENT TRANSPORT PARAMETERS
# Limiting factors for sediment transport          (optional)
#
# Sedimentation time step factor (sedimentation time step =
# flow time step * sedimentation time step factor)
# Maximum depth of fluid elements [m]
# Minimum velocity of fluid elements [m/s]
# Minimum ratio of sediment load fluid element to average sediment
# load at source [kg/m3]
# Basement hardness factor
1.0e4 10.0 0.05 0.10 1.0E2
#
#-----
SEA LEVEL
# Define sea level curve          (optional)
#
# Sea level curve file
#
Haq_plus_dnag.sl
#
#-----
#
COMPACTION
# Enable compaction module          (optional)
# Enter depth of post depositional burial by
# Sediment Water
100 83


```

```
#  
#-----  
--  
#      *** End of input file ***
```

Appendix F: Sedsim Output File (one trace example) in .csv Format

%col	row	x	y	simulated age	gr1(m)	gr2(m)	gr3(m)	gr4(m)	gr5(m)	gr6(m)	gr7(m)	gr8(m)	poro	xpos	ypos	bottom(m)	top(m)	
1	1	1	660850	8484350	8500000	-111500000	1.05202	10.837	9.1575	13.6874	0	0	0	0.325	0	0	-819.17	-784.436
1	1	1	660850	8484350	9000000	-111000000	0	0.036596	5.9165	12.119	0	0	0	0.193	0	0	-784.436	-766.364
1	1	1	660850	8484350	16500000	-103500000	0	0	5.7663	0.98595	0	0	0	0.192	0	0	-766.364	-759.612
1	1	1	660850	8484350	19500000	-100500000	0	0	16.686	0.10764	0	0	0	0.196	0	0	-759.612	-742.818
1	1	1	660850	8484350	20500000	-99500000	0	0.14672	15.589	8.4919	0	0	0	0.209	0	0	-742.818	-718.59
1	1	1	660850	8484350	24000000	-96000000	0	0.43751	1.2374	41.087	0	0	0	0.224	0	0	-718.59	-675.829
1	1	1	660850	8484350	25000000	-95000000	2.7412	22.002	6.4044	0	0	0	0	0.23	0	0	-675.829	-644.681
1	1	1	660850	8484350	25500000	-94500000	0.076932	0	0.39199	0	0	0	0	0.391	0	0	-644.681	-644.212
1	1	1	660850	8484350	28000000	-92000000	0.63416	4.3087	0.88055	0	0	0	0	0.255	0	0	-644.212	-638.389
1	1	1	660850	8484350	28500000	-91500000	14.46	3.5187	0	0	0	0	0	0.355	0	0	-638.389	-620.41
1	1	1	660850	8484350	32000000	-88000000	0.003717	0	0	0	0	0	0	0.355	0	0	-620.41	-620.406
1	1	1	660850	8484350	32500000	-87500000	0.93643	0	0	0	0	0	0	0.356	0	0	-620.406	-619.47
1	1	1	660850	8484350	34000000	-86000000	1.1143	0	0	0	0	0	0	0.356	0	0	-619.47	-618.355
1	1	1	660850	8484350	58500000	-61500000	0	0	0	0	1.554	0	0	0.232	0	0	-618.355	-616.801
1	1	1	660850	8484350	59000000	-61000000	0	0	0	0	3.1868	0	0	0.233	0	0	-616.801	-613.615
1	1	1	660850	8484350	59500000	-60500000	0	0	0	0	3.1683	0	0	0.233	0	0	-613.615	-610.446
1	1	1	660850	8484350	60000000	-60000000	0	0	0	0	3.1878	0	0	0.233	0	0	-610.446	-607.259
1	1	1	660850	8484350	60500000	-59500000	0	0	0	0	3.1885	0	0	0.233	0	0	-607.259	-604.07
1	1	1	660850	8484350	61000000	-59000000	0	0	0	0	3.1884	0	0	0.234	0	0	-604.07	-600.882
1	1	1	660850	8484350	61500000	-58500000	0	0	0	0	3.1901	0	0	0.234	0	0	-600.882	-597.692
1	1	1	660850	8484350	62000000	-58000000	0	0	0	0	3.1908	0	0	0.234	0	0	-597.692	-594.501
1	1	1	660850	8484350	62500000	-57500000	0	0	0	0	3.1914	0	0	0.234	0	0	-594.501	-591.309
1	1	1	660850	8484350	63000000	-57000000	0	0	0	0	3.1703	0	0	0.235	0	0	-591.309	-588.139
1	1	1	660850	8484350	63500000	-56500000	0	0	0	0	3.1824	0	0	0.235	0	0	-588.139	-584.957
1	1	1	660850	8484350	64000000	-56000000	0	0	0	0	3.1847	0	0	0.235	0	0	-584.957	-581.772
1	1	1	660850	8484350	64500000	-55500000	0	0	0	0	15.807	0	0	0.236	0	0	-581.772	-565.965
1	1	1	660850	8484350	65000000	-55000000	0	0	0	0	16.075	0	0	0.238	0	0	-565.965	-549.89
1	1	1	660850	8484350	65500000	-54500000	0	0	0	0	16.52	0	0	0.239	0	0	-549.89	-533.37
1	1	1	660850	8484350	66000000	-54000000	0	0	0	0	17.688	0	0	0.24	0	0	-533.37	-515.682
1	1	1	660850	8484350	66500000	-53500000	0	0	0	0	18.399	0	0	0.242	0	0	-515.682	-497.283
1	1	1	660850	8484350	67000000	-53000000	0	0	0	0	18.421	0	0	0.243	0	0	-497.283	-478.862
1	1	1	660850	8484350	67500000	-52500000	0	0	0	0	18.443	0	0	0.245	0	0	-478.862	-460.419
1	1	1	660850	8484350	68000000	-52000000	0	0	0	0	18.465	0	0	0.246	0	0	-460.419	-441.954
1	1	1	660850	8484350	68500000	-51500000	0	0	0	0	18.487	0	0	0.248	0	0	-441.954	-423.467
1	1	1	660850	8484350	69000000	-51000000	0	0	0	0	18.509	0	0	0.249	0	0	-423.467	-404.958
1	1	1	660850	8484350	69500000	-50500000	0	0	0	0	13.863	0	0	0.251	0	0	-404.958	-391.095
1	1	1	660850	8484350	70000000	-50000000	0	0	0	0	6.4945	0	0	0.253	0	0	-391.095	-384.6
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1	1	1	660850	8484350	1.02E+08	-18000000	0	0	0	0	6.2241	0	0	0.293	0	0	-191.425	-185.201
1	1	1	660850	8484350	1.03E+08	-17500000	0	0	0	0	9.5893	0	0	0.295	0	0	-185.201.	


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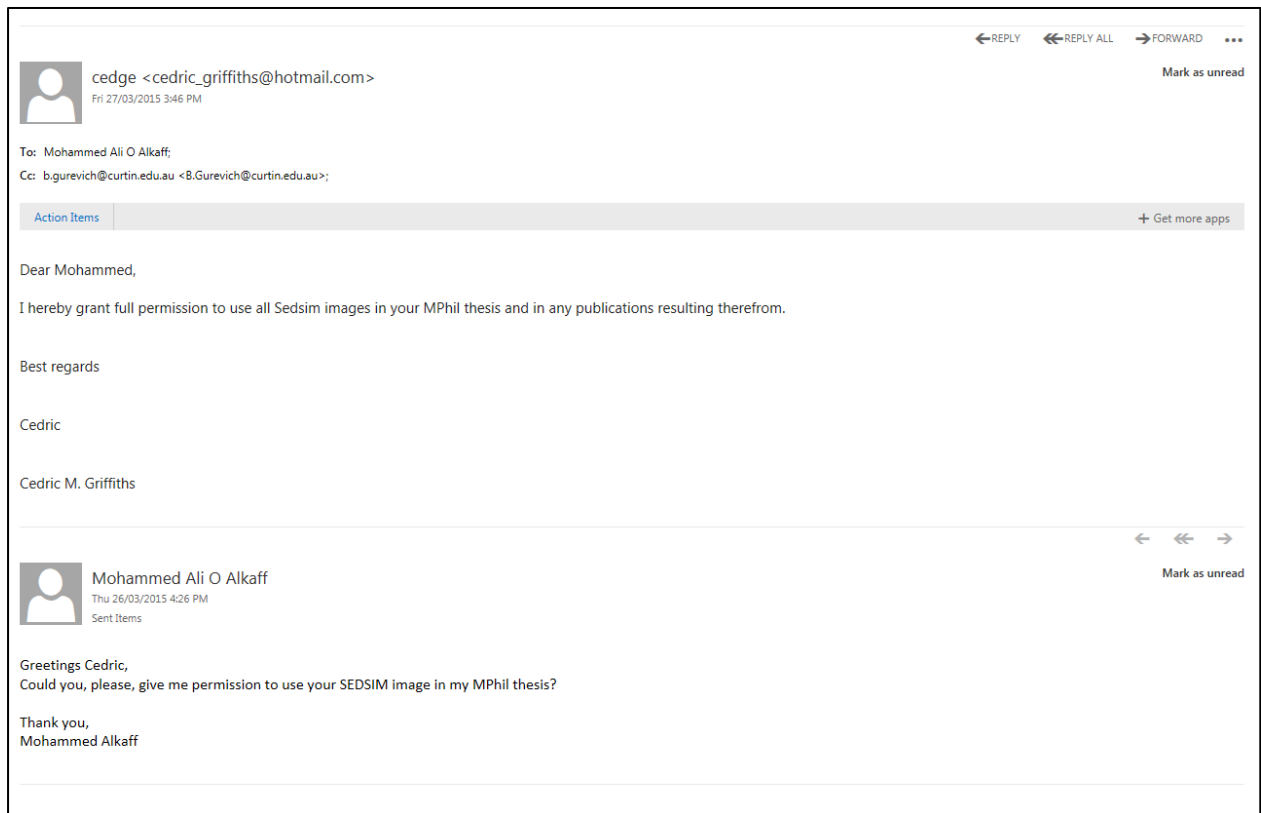
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Appendix J: SegyMAT Copyright Statement

SegyMAT

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Appendix K: Depositional Environment Description

Formation	Thickness (m)	Age	Depositional Environment	Lithological Description	Visual Porosity From Core
Hibernia Formation	108.0	Palaeocene to Eocene	Shore face and shallow marine	Limestones: white, cream, very light grey, Firm to hard, Sub-blocky to blocky frameworks.	
Upper Heywood Formation	45.7	Late Albian to Turonian	offshore marine	Claystone: light to dark green and grey, soft to firm, slightly to moderately calcareous, occasional very fine pyrite, glauconite and micro mica.	
Upper Heywood Reservoir Layer A	9.6	Late Albian	Upper offshore	A waste zone of claystones and siltstones grading to sandstone: - claystones: light to dark green, grey, soft to firm, slightly to moderately calcareous, occasionally fine to very fine glauconite. - siltstones: very dark grey, sand and glauconite in part, very clay rich. - sandstones: dark grey to very dark brown, moderately hard, fine to very fine, silty in part, subrounded, glauconite, up to 60% of matrix content.	3%
Upper Heywood Reservoir Layer B	9.8	Late Albian	Upper offshore/Lower shoreface	Sandstones (part of the main reservoir interval): very dark brown, fine to very fine, occasional medium to quartz grains, subrounded to rounded, moderately to well sorted, slightly bioturbated, traces of pyrite and glauconite, up to 30% matrix content, decreasing upward GR signature (coarsening upward cycle) capped by sharp GR increase (flooding surface).	10%
Upper Heywood Reservoir Layer C	10.2	Late Albian	Upper offshore/Lower shoreface	Sandstones and siltstones (part of the main reservoir interval): - sandstones: very dark brown, fine to very fine, subrounded to rounded, well sorted, traces of pyrite, up to 20% glauconite, up to 30% matrix content. - siltstones: very dark brown, mottled, sandy in part, moderately hard, micro micaceous. decreasing upward GR signature (coarsening upward cycle) capped by sharp GR increase (flooding surface).	10%
Upper Heywood Reservoir Layer D	14.1	Late Albian	Upper offshore	Claystones and silty sandstones (their zone or potential seal): - claystones: very dark brown to black, mottled, silty, organic rich. - sandstones: dark brown to very dark brown, very fine to very coarse, poorly sorted, glauconitic, up to 50% clay matrix, occasional clean silty laminae.	3%
Denticulata Sandstone	8.3	Middle Albian	Lower shoreface	Sandstones (part of the reservoir section): dark grey to dark brown, fine to medium, occasional pebbles, moderately to poorly sorted, clay and glauconite matrix supported, friable to relatively unconsolidated frameworks	2% to 14%
Tetracantha Sandstone	1.0	Early Albian	Lower shoreface	Sandstones: dark green grey, soft, fine to very fine, moderately sorted, subrounded to rounded, slightly glauconitic and calcareous, minor argillaceous matrix.	fair
Basement					